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DETERMINATION OF PLATE TECTONIC MOTION FROM DOPPLER OBSERVATION--ETC(U)
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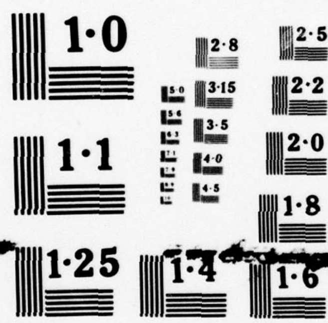
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REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER NSWC/DL-TR-3884	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) DETERMINATION OF PLATE TECTONIC MOTION FROM DOPPLER OBSERVATIONS OF NAVY NAVIGATION SATELLITES		5. TYPE OF REPORT & PERIOD COVERED Final rept.,
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) R. J. Anderle		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS Naval Surface Weapons Center (K10) Dahlgren, Virginia 22448		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS HM0027-78-C002
11. CONTROLLING OFFICE NAME AND ADDRESS Defense Mapping Agency Headquarters Washington, DC 20305		12. REPORT DATE August 1978
		13. NUMBER OF PAGES 67
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)		15. SECURITY CLASS. (of this report) UNCLASSIFIED
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

12 66p.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Continental Drift/Plate Tectonic Motion
Doppler Point Positioning
Navy Navigation Satellite
World Geodetic System
Geoceiver

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Doppler observations of Navy Navigation Satellites have yielded precisions in the determination of rates of change of station position of 2 cm/yr, based on data sampled over a 14-yr period, and 3 cm/yr for nearly continuous data over a 6-yr period. The accuracy of the determination is better than 10 cm/yr in horizontal position and 15 cm/yr in height for either data span. A number of changes in data acquisition and data reduction are proposed which will improve the accuracy of the results and lead to the determination of plate tectonic

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motion from this data.

The computed latitude rate for Australia, which is 12.1 ± 1.5 cm/yr, is consistent with geologic estimates. Maintenance of the base station network is critical to obtaining such results for other components of station position, other geographic areas, and other time periods.

FOREWORD

Doppler observations of Navy Navigation Satellites have been used to determine the positions of navigation beacons, interdatum relations and geocentric positions of isolated sites, and major datums since 1964. The calculations have also provided the motion of the earth's spin axis with respect to the crust since 1969. Periodically, coordinates of the worldwide base stations used to compute the satellite orbits are determined from those orbits (a circular kind of computation) to determine the stability of the coordinate system and identify inconsistencies in the computational procedure. This report examines the results of these computations to evaluate the possibility of using the data to determine plate tectonic motion.

The precisions achieved to date in the calculation of positions of Doppler observing stations are sufficient for determining plate tectonic motion, but inaccuracies in the collection and computational procedures render the results unreliable. It is suggested that continued data collection under controlled conditions and recomputation of station positions with data collected to date could provide useful results on plate tectonic motion.

Satellite ephemerides used in this study and observational data have been provided by Caroline Leroy of the Defense Mapping Agency Topographic Center since 1973. Computation of station positions was made by Teck Judd, while station coordinate changes were computed by Natalie Krohn, both of the Naval Surface Weapons Center.

Released by:

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INTRODUCTION

The Navy Navigation Satellite Program was established in the late 1950s to provide the real-time position of ships to 100-m accuracy. As this goal was being approached, it became evident that post processing of data could be used for geodetic applications. A project to develop this capability was established in 1962 with a goal of 10-m accuracy. Positions of navigation beacons, isolated tracking stations, datum origins, and interdatum ties were found to 50-m accuracy in 1963, improving to about 1-m accuracy in 1972.[1] The improvement in accuracy was achieved primarily by refinements in the determination of the effects of the earth's gravity field on satellite orbits, except for the change in 1969 to the real-time determination of the motion of the earth's spin axis with respect to the crust.[2] Since that time, changes in the computational model have primarily centered about the development of consistent station coordinates for the observing stations.

In 1968, a review of results to that time indicated that 20 yr of intermittent or continous determinations of station positions would yield continental drift to an accuracy of 15 cm/yr or 5 cm/yr, respectively.[3] Since only preprints of the test of that report were distributed, it is reproduced as Appendix A for historical perspective and to document the procedure for establishing the effective position of the antenna array. A subsequent review showed that projection to be pessimistic due to refinements incorporated in the calculations in the interim period.[4] A standard error of 10 cm/yr was found for a period of 2.5 yr, and an accuracy of 2 cm/yr was predicted for continuous observations over a period "longer than 5 years" (7 yr for the data given). Continuous computations of positions have now been completed at nine locations. The purpose of this report is to reexamine the potential of Doppler observations of Navy Navigation Satellites to determine plate tectonic motion on the basis of these computations and others that were made to monitor the stability of the coordinate system and detect computational inconsistencies.

OBSERVING NETWORK

Results of computing the positions of 22 of the sites shown in Figure 1 (Appendix B) are discussed in this report. The break in operation of the stations shown in the figure for the 1970-1971 time period was caused by the change in the equipment to count Doppler in contiguous intervals of about 20 sec in length rather than a 1-sec interval starting each 4 sec. This change required a change in data representation from frequency to range difference. (The break in operations was

shorter than that shown in the sketch.) The 22 sites are all those shown operating in the 1972.0-1978.0 time period, except Grasse and Wake operated for only a brief period. The figure shows that antenna changes were made at six of these sites during that time period and that station operations were not conducted during a substantial protion of the period for six additional sites. In addition, antennas are switched intermittently at three of the sites (310, 320, and 330). Therefore, a continuous record of data is available from only eight sites for which no record of an antenna change has been recorded during the 6-yr period. However, survey records between old and new antennas at stations 116, 310, 320, and 330 appear to be quite reliable, and the difference between the station 13 and 27 antennas was based on 5 wk of simultaneous satellite observations at the two sites. Therefore, it is believed that the continuous record of observations may be reliable for at least 14 sites during this 6-yr period.

COMPUTATIONAL PROCEDURES

Satellite orbit computations were based upon a least-squares solution for six constants of integration of the orbit of one of the Navy Navigation Satellites, an atmospheric drag scaling factor, and the components of pole position using 2 days of observations from the observing network. (In a few of the computations at the beginning of the 1964-1978 time period, longer time spans of data were used, in which case additional drag parameters were included.) The parameter set also included a refraction scaling parameter and oscillator frequency offset for each pass and the coordinates of new observing stations. The gravity field was defined by the NWL-9B geopotential coefficients until 2 January 1973, at which time the NWL-10E coefficients were used. The coordinates of base stations were nominally defined as the NWL-9D set until October 1977 when the NWL-9Z2 set was introduced. However, each of these coordinate sets was extended to include values for new stations, as they became available, and occasionally to correct previous additions. Computations for observations made before 1972 were generally done in the 1970-1972 time period in connection with the revision of the Department of Defense World Geodetic System 1972. The remaining computations produced the precise ephemerides used by the Defense Mapping Agency and other agencies for percise positioning. The same observations used to determine the satellite ephermeris were then used to determine the position of the ground station with respect to the ephemeris. Five days of observations are used to determine the position of the station. Also included in the solution was a scale factor for tropospheric refraction and the oscillator frequency offset for observations made after October 1975 and for results given for 1972. In the computations made prior to October 1975, the tropospheric refraction was held fixed. The 1973 results in this report were computed after the computer program was changed to include the refraction parameter.

In 1977, errors were found in the calculation of the effect of the travel time of the signal from the satellite to the receivers. The error did not exist in the programs used to compute the satellite ephemeris but did exist in the two programs used at the Naval Surface Weapons Center (NSWC) to compute ground station position using an earth-fixed ephemeris. To compensate for the error, the following corrections were added to the computed longitudes of stations:

Doppler stations:	+$0''.097$
Tranet stations*:	−$0''.009$
Geoceivers**:	+$0''.030$

The computer program used to process geoceiver data was corrected 11 May 1977 at NSWC. The Geodetic Survey Squadron of the Defense Mapping Agency Topographic Center, which uses a program based on the same computer code, also tested the effect of the program change and found the revised longitudes to be 0.79$\pm$.06 m larger for station latitudes ranging from 6°S to 65°N, which is a slightly smaller correction.[5]

A linear least-squares fit was made to the 5-day solutions for each component of position of each station for the period 1972.0-1978.0 and for other cases of interest. The 5-day solutions were weighted in accordance with the number of passes in the solution. Solutions which were based on fewer than four passes were excluded from the least-squares fit. Three iterations of a filter were made to reject solutions that departed from the linear fit by more than 2.5 times the standard deviation of the residuals of fit.

RESULTS

Table 1 (Appendix C) shows the changes in coordinates of 12 of the 14 stations for which continuous data is available over almost all of the 6-yr period 1972.0-1978.0. Results for Maine and Minnesota are excluded from the table. Large rates obtained for one or more components of position of these two stations may be due to unusually large errors in the nominal coordinates of the station used in the solution or to improper handling of results from different antennas used at the stations. The standard errors of the rates are close to those predicted from earlier tests with shorter data spans, particularly since only part of

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* Doppler tracking system (TRANET) is a network of receiving stations and other facilities used to acquire and process Doppler data from near-earth satellites.

** Unless processed in the computer program, used to process TRANET data.

the data in 1972 was processed for the stations and no data for 1973 was processed for three of the stations listed in Table 1 and for the two stations excluded from the table. The rates of change of latitude are reasonable in most cases. Even the rate of change of Japan and the Phillipines with respect to Australia is in the expected direction. The rate of change of the North American station is consistent in direction and magnitude with the drift of the mean pole observed classically. However, the longitude and height rates are unreasonable for a large percentage of the stations, as they were for shorter data spans.

Since the anomalous rates in longitude and height are believed to be due primarily to the use of a fixed tropospheric model in the calculation of refraction effects for data spans prior to 1972 and in the 1973-1975 time period, the rates were recomputed using positions computed for 1972, 1976, and 1977 data. Results of these calculations are given in the third column of rates in Table 2. Results are also given for all stations based on the data spans 1973.0-1975.5 in the first column as reported by Anderle[4], based on 1972-1978 data span in the second column (from which Table 1 was abstracted), and based on the 1964-1978 data span in the fourth column of rates. The increase in data span from 2.5 to 6 yr (columns 1 and 2) generally resulted in reduced rates in latitude and height rates, although there are exceptional cases such as the latitude rates for the Alaskan station and the height rates for the European and Maryland stations. The longitude rates increased about as often as they decreased with the increase in span. The omission of the 1973-1975 data (columns 2 vs 3) did not, in general, significantly alter the magnitudes of the rates compared with the standard errors. The increase in data span from 6 yr to include the scattered data back to 1964 (colums 2 and 4) generally resulted in a reduction of the rates. Only a few longitude rates for the 1964-1978 span exceed 10 cm/yr, and this is considerably better than was expected in 1968, as cited in the introduction. However, the use of the long data span introduces many additional changes in antenna locations, for which documentation becomes poorer for earlier time periods when accuracy requirements were less stringent and which affect the result for individual stations. But more importantly, the variations in length of occupation of individual stations make comparison of rates of little value, since either geophysical effects on station locations or artificial effects of anomalies in computational procedures will yield different relative rates for stations that observe in different time periods. Table 3 is extracted from Table 2 to summarize the results for those stations that were occupied a substantial portion of the 14-yr period from 1964-1978. But the table shows wide variation in the number of solutions either available or processed for these stations. The Maryland station was closed before the end of the period, and the Alaska and Greenland antennas were moved to unsurveyed locations before the end of the period, while 1973 data was not processed for four other stations. There is uncertainty about changes in antenna locations at several of the sites.

A puzzling result is the negative bias in the longitude rates for the 1972-1978 data spans (Tables 1 or 2a). If the computations were done properly, such a bias could not occur because the computed satellite orbit is fitted to the observations with the station longitudes held fixed, and then the station longitudes are computed from that orbit. The only explanation for the result that comes to mind is that the error in the positioning programs is gradually changing the coordinate system as new sites are added to the network and as positions are computed for new antenna locations for old sites. But despite this and other problems cited above, the computed positions of stations based on 5 days of observation of one satellite are still obtained with a consistency of 103 cm, 76 cm, and 116 cm in longitude, latitude, and height, respectively, as shown in Table 4 for the 6-yr period 1972-1978. The consistency over the 14-yr period 1964-1978 is similar. Furthermore, the precision and accuracy being obtained for geophysical applications are considerably better than forecast previously. Since it is unlikely that measured rates of change of station coordinates would be too small due to observational or computational error, the actual rates provide a worst-case estimate of the accuracy. Table 1 shows that 6 yr of nearly continuous data has yielded precisions of 3.5, 3.0, and 3.6 cm/yr in rate of change of station longitude, latitude, and height, respectively, and accuracies of better than 12.5, 8.4, and 18.8 cm/yr, respectively. Table 3 shows that 14 yr of intermittent data yields precisions of 1.9, 1.7, and 1.6 cm/yr in rate of change of station longitude, latitude, and height, respectively, and accuracies of better than 11.0, 8.1, and 15.1 cm/yr, respectively. The precisions are optimistic, particularly for very short data spans, because they neglect nonlinear effects or errors that are correlated with time. Correlation of the station coordinate changes may be seen by inspecting the individual solutions that are given in Figure 2 for each site. On the other hand, both precision and accuracy, particularly in height and longitude, can be improved by improved processing techniques and by other methods described below.

USEFULNESS OF THE DOPPLER TECHNIQUE

With the potential of the Very Long Baseline Interferometer (VLBI), Lunar laser and Lageos laser techniques to determine plate tectonic motion to high accuracy after a brief period at a site, it is reasonable to question whether any special effort should be pursued to accomplish the same task using Doppler data when 5 yr or more of nearly continuous Doppler data would be required. A number of factors favor the duplication of effort. Of course, the usual desire exists for independent verification of a difficult measurement. Second, the relatively low cost of the equipment and relatively lower skill level required in operation could encourage more international participation, which would make results available from regions which might otherwise be inaccesible or expensive to occupy. Third, weather in many regions is not suitable for

laser operations. Finally, Doppler data, little of which has been processed for this purpose, already exists for sites on many of the plates. Figure 3 shows the sites discussed in this report, the rates and standard errors of rates of station motion calculated from the 1972-1978 span of data, and the zones of upwelling and downwelling sketched from various reports. In addition to these sites, geoceiver data exists in the Defense Mapping Agency library, and Doppler data has been taken by agencies in many other countires at a variety of locations. Therefore, results could be obtained earlier for numerous geographic locations using Doppler data than using the more precise data.

POTENTIAL IMPROVEMENTS IN THE DOPPLER RESULT

Many steps can, and some will, be taken to improve the precision and accuracy of determining plate tectonic motion from Doppler observations of Navy navigation satellites. These will be discussed in the order listed in Table 5 from the point of view of their significance with respect to improving current results, the cost of implementing and operating under the revision, whether the change will be made in the normal course of events or need an administrative decision to bear the additional cost, and whether technical studies are required to assess impact before the decision is made. Costs of changes in the orbit or positioning techniques are estimated as low, moderate, or high compared with the normal cost of the respective computations, while the other costs are rated relative to total computational costs.

Most of the base stations are equipped with rubidium oscillators, but most of the geoceivers and other equipment are equipped with crystal oscillators. Figure 4 shows the oscillator stability as a function of time span of measurement for geoceiver oscillator specifications, JMR* specifications, measured values on a cesium oscillator at NSWC, and a rubidium oscillator at the Jet Propulsion Laboratory. (The stability of the geoceiver and JMR oscillators was extrapolated from the point values shown parallel to Allen variance curves for other oscillators.) Reading the slanted grid lines labeled at the top of the chart for averaging times of 5 to 10 min, it is evident that errors of 20 to 40 cm could build up in range difference measurements made with crystal oscillators. But this is the critical time interval for observations of satellites at altitudes of about 1000 km because the integrated deviation of the actual frequency over this time period from the frequency solution for the 20-min pass will directly alias into the solution for the coordinates of the station with an amplification factor of greater than 5. (A random error of observation over 30 min of 10 cm corresponds to about a 50-cm standard error in station position. It is believed that a systematic error may be more serious.) The oscillators are probably better than the specifications given, but the quartz oscillators appear to be a significant source

* JMR Instruments, Inc.

of error, while the rubidium oscillator would produce errors smaller than those due to jitter in the phase measurement (11 cm in the geoceiver specifications). While the error due to the quartz oscillator is still not large compared with the orbit uncertainty under good geometry conditions, a large percentage of passes occur at the lower elevation angles where the instrument error dominates the orbit error. Improvement in receiver accuracy would mean fewer satellite passes would have to be observed to average out instrument error. A study is being conducted to quantify this conclusion.

Availability of data from additional stations by other agencies and countries would be a considerable aid in isolating errors and densifying results. But the most important factor is maintaining a fixed base network without changes in antenna locations. Since there is no current program for Doppler determination of plate tectonic motion, station deployment is determined solely on the basis of the requirements of the mission being conducted. Therefore, any program established would have to bear the cost of continued operation of base stations not required for other purposes. A large number of base stations are desirable to average out the effects of motion of individual plates on the computed orbits.

The principal error in the satellite orbit is due to uncertainties in the gravity field. Refinements in the field are being made with the use of GEOS-3 altimetry data, which would be inexpensive to implement, but large quantities of data from Navy Navigation Satellites will probably have to be processed with the altimetry data to achieve improvement in orbit accuracies currently being achieved. Such processing would be expensive. A larger number of gravity coefficients would increase processing costs by a low or at worst a moderate amount. Miscellaneous changes are being made in the computations to account for the effects of atmospheric and ocean tides on the force field and for the effect of solid earth tides on station position. These will incur negligible costs in operation but will not yield significant improvement until gravity and instrument errors are reduced. Processing data for additional satellites will increase precision by an amount inversely proportional to the square root of a number of satellites but more importantly will shorten the time span required for a given precision, thus eliminating sources of systematic error due to changes in station array. During some time periods, these calculations have been made but not used in positioning. Reprocessing old data to recompute the orbits would reduce a major source of error introduced by changes in coordinates of base stations but would be expensive. Orbit calculations based on drag-compensated satellites will eliminate another source of error in satellite orbit and compute pole position.

The program used to compute station positions, "DARCUS," is undocumented and has incurred extensive changes over the original code.

Recoding would facilitate configuration control and give greater confidence in the results but would be expensive. An alternative is the use of another program that is available, "CELEST DARCUS," which is somewhat more costly in operation and may require some interfacing. A tropospheric refraction bias parameter exists in all programs at NSWC, and its use should improve heights and probably longitudes of any sites for which recomputations are performed at negligible cost. A correction for second-order ionospheric refraction could improve results. Although simulations made to date have not indicated that the correction is significant for other applications, the problem should be reexamined for this purpose. It seems likely that long period changes in solar activity could appear as long period changes in computed station height. The first order ionospheric refraction recorded by the geoceiver would be useful for this purpose, while model data should be adequate for old data and other base stations. Combining observations made over 30-sec intervals to construct 60-sec data, after first filtering the 30-sec data to detect bad data, offers hope for some improvement in precision. Going further and treating the data as biased ranges in the manner normally used by Brown[6] yields an increase in precisions of a factor of three, which would be very valuable if the oscillator stability is sufficiently good to support the technique. Both of these approaches are being tested. Consideration of the orbit error in the solution for station coordinates would give lower elevation passes their proper weight in the solution, although common orbit biases for neighboring stations such as employed in the Brown[6] short arc approach appear to have limited usefulness for the generally widely separated base stations. The comments made earlier about using data for satellites and more stations and about reprocessing old data apply more in this section, except that the cost is small compared with the orbit computation. Some recomputations will be performed in any case to isolate the cause of the secular change in the longitude of the station net.

Survey records will be reexamined in a few cases, but a continuing liaison activity would be required to insure that undocumented changes are not made to antenna installations as personnel change over the relativley long period of time that would be required for Doppler determination of plate motion. Computations of rate of change of station position could be improved by computing relative rates of change of station position for station pairs of groups over identical data spans. This decreases the precision of the determination but increases the accuracy. The difficulty is in deciding whether to consider a surveyed change in antenna position to have been measured perfectly or to be a break in operation of the station. Even if realistic error estimates could be made for the survey, a solution for station rate with the survey connection given that a-priori uncertainty would probably result in a fit to errors from other sources. A limited effort will be made in these directions as part of the evaluation of the stability of the coordinate system.

PLANS AND RECOMMENDATIONS

A number of actions are being taken to improve the accuracy of determining coordinates of stations making Doppler observations of Navy Navigation Satellites. These actions, noted by "N" in the fourth column (Special Effort Required) of Table 5, may result in the determination of plate tectonic motion from these observations. To increase the probability of success, obtain results for more geographical areas, and achieve the results more quickly, the actions noted by "Y" in that column of the table should be taken.

A decision on most of these items is not time-critical, but it is impossible to totally compensate computationally for changes in the base station network. Sites such as Australia and Brazil, which are distant from other base stations and have the longest period of operation using the same antenna, are particularly critical to validation of the stability of the coordinate system and of great importance to plate tectonics studies. Note that computed latitude rate for Australia relative to the mean coordinate system of the Doppler base stations is 12.1 ± 1.5 cm/yr over the last 5 yr and 12.7 ± 1.0 cm/yr over the last 15 yr. These values are consistent with the motions of the continent reported for geologic time periods. It is recommended that every reasonable effort be made to maintain the current base station network to obtain valid data for other components of position, other geographic areas, and other time periods.

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APPENDIX A

ACCURACY OF DETERMINATION OF CONTINENTAL DRIFT FROM DOPPLER SATELLITE OBSERVATIONS

ACCURACY OF DETERMINATION OF CONTINENTAL DRIFT FROM DOPPLER SATELLITE OBSERVATIONS

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March 1968

Prepared for presentation at the 1968 Annual Spring Meeting of the American Geophysical Union, April 8 through 11, Washington, D. C.

ABSTRACT

Doppler observations over a three year period on polar orbiting satellites were analyzed to determine the extent to which the movement of tracking sites could be defined. The motion of sites with respect to the major western hemisphere land masses could only be determined to an accuracy of about 100 cm/year. An accuracy of 5 cm/year appears achievable for an average over a 10-20 year period if the observation program is continued.

BACKGROUND

Runcorn's studies [1962, 1967a, 1967b] have intensified interest in relating horizontal motions of the continents to large-scale convection currents in the earth's mantle. Supporters of the relationship include Allan et al [1967], Bott [1967], Orowan [1967], and Oxburgh [1967]. Kaula [1963] and MacDonald [1964] not only question the validity of the convection hypothesis but they and other scientists also have reservations about the evidence indicating the existence of continental drift, which is required to support the convection theory. Creer [1967], Girdler [1965] and Bullard et al [1965] are among those who have advanced data supporting continental drift while Hospers [1967], Lyustikh [1967] and MacDonald [1963] have proposed alternate interpretations of the data. Satellite observations offer a possible additional source of information on the motions of the continents. Such data have been reported to be capable of positioning the observing station to 10 m accuracy [Anderle 1967, Clancy 1967]. While such accuracy does not appear to be adequate to resolve the question of the existence of a 1 cm/year drift, the rapid advancements in dynamic satellite geodesy have made it appear useful to evaluate the positioning accuracy of the most recent data more carefully.

PROBLEM AREAS

This study is based upon satellite observations made by the U. S. Navy Doppler system which, as described by Newton [1967], has an instrument accuracy of about 10 meters for two dimensional positioning of the observing site from data taken on a single satellite pass. Since thousands of satellite passes are observed each year at each instrument site, the mean station position could be considerably better to the extent permitted by computational techniques. The limiting computational factor in the past has been the accuracy of the determination of the gravitational field of the earth. Uncertainties in the gravity field produce errors in the computed satellite orbit which are transferred as errors in the computed satellite orbit which

are transferred as errors in the computed position of the observing site. Additional computational errors arise from the neglect of the effects of solid earth tides on the shape of the earth and the neglect of the effects of ocean tides. Effects of solid earth tides on the force field about the earth are only included in the most recent computations. The principal effect of these computational errors will be to produce random error and a fixed bias in relative station position. However, should relative station motions be found, it seems unlikely that conclusive proof could be could be established that the measured motions are not due to computational errors. On the other hand, the possibility that computational errors would accidently cancel any actual station motions seems quite remote. Therefore, analysis of the satellite data could produce evidence refuting the existence of continental drift at the present time, but any evidence favoring drift might be debatable. An additional difficulty in the use of satellite observations for the intended purpose is uncertainty in antenna position. Since two antennas separated by a few meters are used in the correction of ionospheric refraction effects, the effective station position is difficult to define and may in fact vary according to the geometry of a particular pass of the satellite over the station. Errors from this source can also be expected to affect only the random error of observation so long as the antennas are not moved. While it is possible to select data based on the same satellite frequencies, it is not a trivial matter to have assurance that the precise antenna locations are unchanged. In the early development of the Doppler system antenna experiments might have caused changes in station position exceeding a meter. Therefore, the older observations are not used. Even currently, if construction at a station requires a change in antenna location, the accuracy of the repositioning may not exceed 30 cm. However, the record of antenna positions suggests that a repositioning accuracy of about 1 cm can be achieved for several sites.

PROCEDURE

The source data for these calculations were normal equations for geodetic and orbit parameters formed for Doppler Satellite observations in the course of a general geodetic solution. Each normal equation was based on observations made in either an 8 or 16 day time span at 13 common sites and at up to 5 additional sites which were usually different for different time spans. The parameters of the equations included over 200 gravity coefficients, the coordinates of all the observing sites, instrument biases (implicitly), and orbit parameters which included the six orbit constants, one for solar radiation pressure, one to scale the drag force and two extraneous parameters. The extraneous parameters were used to account for the dominant effect of resonance effects due to gravity coefficients of 24th to 28th order. The normal equations for satellites of seven orbital inclinations were combined and solved to produce a set of geodetic parameters referred to

as NWL-8D. For purposes of this study the individual normal equations for polar satellites were solved separately, employing certain constraints, to yield solutions for 8 to 16 day time spans. The solutions are given as deviations from the NWL-8D solution. Constraints were generally imposed to force most of the gravity coefficients and the positions of stations in North America, South America, and Greenland to conform with the NWL-8D results. The second degree zonal and tesseral gravity coefficients were generally left free in the solution. The effects on the solution of small changes in the number of station and gravity parameters were tested in special computer runs and found to be negligible. The study was restricted to observations of polar satellites in order to use homogeneous data for the maximum available time span. While data for nonpolar satellites were available for earlier time periods, the effects of remaining errors in the gravity field are different for satellites having different orbital inclinations which would lead to a spurious difference in relative station positions between the older and the more recent observations.

Corrections for changes in antenna locations were made on the assumption that the electrical center was .163 of the distance from the 400 mc antenna to the 150 mc antenna. The correction is based on the pair of frequency equations

$$f_1 = f_{\tau 1} - \frac{f_{\tau 1}}{c} \dot{r}_{\upsilon} + \frac{a_{\upsilon}}{f_{\tau 1}}$$

$$f_2 = f_{\tau 2} - \frac{f_{\tau 2}}{c} \dot{r}_{\infty} + \frac{a_{\infty}}{f_{\tau 2}}$$

where f_1 and f_2 are the frequencies received on the 150 and 500 mc antennas, respectively.

$f_{\tau 1}$ = 150 mc,

$f_{\tau 2}$ = 400 mc,

c = velocity of light,

$\dot{r}_{\upsilon}$ and $\dot{r}_{\infty}$ are the range rates with respect to the positions of the 150 and 400 mc antennas, respectively, and $a_{\upsilon}/f_{\tau 1}$ and $a_{\infty}/f_{\tau 2}$ are the first order ionospheric refraction corrections at the positions of the 150 and 400 mc antennas, respectively.

An analog combination of these two frequencies is performed at the station in order to eliminate the refraction term. The following combination, or a known multiple of it, is recorded:

$$\frac{f - Rf_1}{1 - R^2} = f_{\tau_2} - \frac{f_{\tau 2}}{c}\mathring{f}_\infty - \frac{f_{\tau 2}R^2}{c(1-R^2)}(\mathring{f}_\infty - \mathring{f}_\upsilon) + \frac{a_\infty}{f_{\tau_2}} - \frac{a_\upsilon}{f_{\tau_2}}\ (1 - R^2)$$

where $R = f_{\tau_1}/f_{\tau_2} = 150/400$.

The first two terms on the right give the refraction corrected frequency expected at the high frequency antenna location "B." Setting $\mathring{f}_\upsilon \sim \mathring{f}_\infty + \frac{\partial \mathring{f}}{\partial x}(x_\upsilon - x_\infty)$, the third term yields the correction $R^2/(1 - R^2)$ of the distance from location B to location A. The final term, the difference in refraction at the two positions, is neglected.

RESULTS

A total of 25 separate solutions for station coordinates was computed using polar satellite observations made in 8 or 16 day time spans between late 1963 and early 1967. The orbital elements for the different satellites are given in table 1. Figure 1 shows the solutions obtained for the site in Misawa, Japan, holding the positions of sites in Greenland, North America and South America fixed at values found in the NWL-8D solution. A trend in the longitude of the station can be noted, although the statistical significance of the trend is not apparent. In order to provide guidance on the statistical significance of the results, a least squares fit of a straight line was made to the solutions for each coordinate of each permanent station. Solutions based on fewer than 21 satellite passes were ignored. The rms residuals, the slope and the standard error in the slope are given in table 2 and graphed in figure 2. The drift of the stations is generally not significant compared to the accuracy of the determination which is about 100 cm/year for the stations which made the most complete set of observations. Although there are a few cases where the computed drifts exceed the standard error in the drift, the biases are probably due to a defect in the statistical model: The individual solutions were assumed to be of equal quality while in fact the older solutions appeared to have a larger scatter than those based on more recent and more numerous solutions. The overall standard deviation of an individual solution of about 4 meters is a factor of two or three better than that reported a few years ago [Anderle 1967].

SUMMARY

The accuracy obtained in the determination of station movement is not sufficient to either support or refute the conclusion that the continents are drifting. However, the accuracy achieved is better than has generally supposed to be possible. Since the accuracy of the

drift determination varies linearly with the time span of observation, an increase in time span of observation from the present 3 years to 20 years would improve the accuracy of the determination to 15 cm/year. The present study is based on about six months of data observed on one or another satellite during the three year period considered; if the same proportion of data were processed for the 20 year period, the accuracy would be further improved to about 5 cm/year. Still better accuracy could be achieved by virtue of a modest additional improvement in accuracy or by the use of a larger proportion of the data obtained. Therefore, meaningful results would probably be obtained in about 20 years if the observation program continues.

ACKNOWLEDGEMENTS

The Doppler satellite observations made under arrangements established by the Doppler Satellite Office, Pt. Mugu, were provided by the Applied Physics Laboratory, Johns Hopkins University. Arrangements for terrestrial surveys of the antennas were made by the Naval Oceanographic Office. Reduction of the data and formation of the normal equations upon which this study was based were directed by S. J. Smith and R. W. Hill with the guidance of C. J. Cohen. C. H. Seay performed most of the final computations for this study.

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TABLE 1

PRINCIPAL ORBITAL ELEMENTS

Satellite	Inclination	Perigee Height(km)	Eccentricity
1963 38C	89.9°	1067	.004
1963 49B	90.0°	1056	.003
1964 26A	90.5°	864	.007
1965 48A	90.0°	1025	.007
1965 109A	89.1°	912	.010
1966 24A	89.7°	888	.016
1966 41A	89.9°	856	.008
1966 76A	88.8°	1048	.003

TABLE 2

RESULTS OF LEAST SQUARES SOLUTION

Station	No. of Solutions	Span of Data(yrs)	Rate of Change of Position (cm/yr)			Standard Error in Rate (cm/yr)			Residuals of Fit (cm)		
			Radius	Lat.	Long.	Radius	Lat.	Long.	Radius	Lat.	Long.
Seychelles Is.	9	2.2	342	17	- 23	125	102	244	306	251	564
Philippine Is.	11	2.7	-385	99	-280	85	139	137	230	377	373
Samoa	12	2.7	- 43	23	-224	63	63	236	206	207	771
England	21	2.2	- 12	16	-373	74	64	215	156	137	458
Australia	16	3.3	- 35	106	-103	91	74	268	337	273	995
Hawaii	18	3.3	-104	-17	- 91	117	93	201	427	336	730
So. Africa	20	3.3	68	61	35	71	54	94	288	220	382
Japan	19	3.3	- 15	-59	170	75	58	87	290	222	334
MEAN	16	2.9	- 23	31	-111	88	81	156	280	253	576

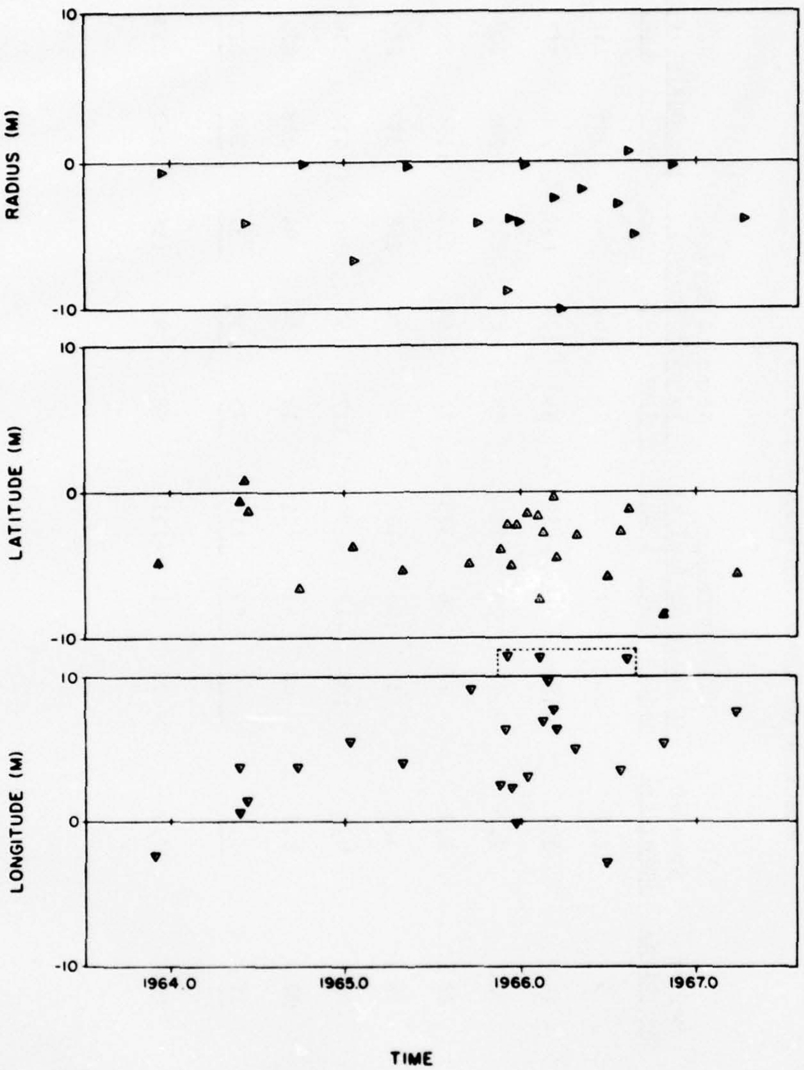

Figure 1. Positions Computed for Japan

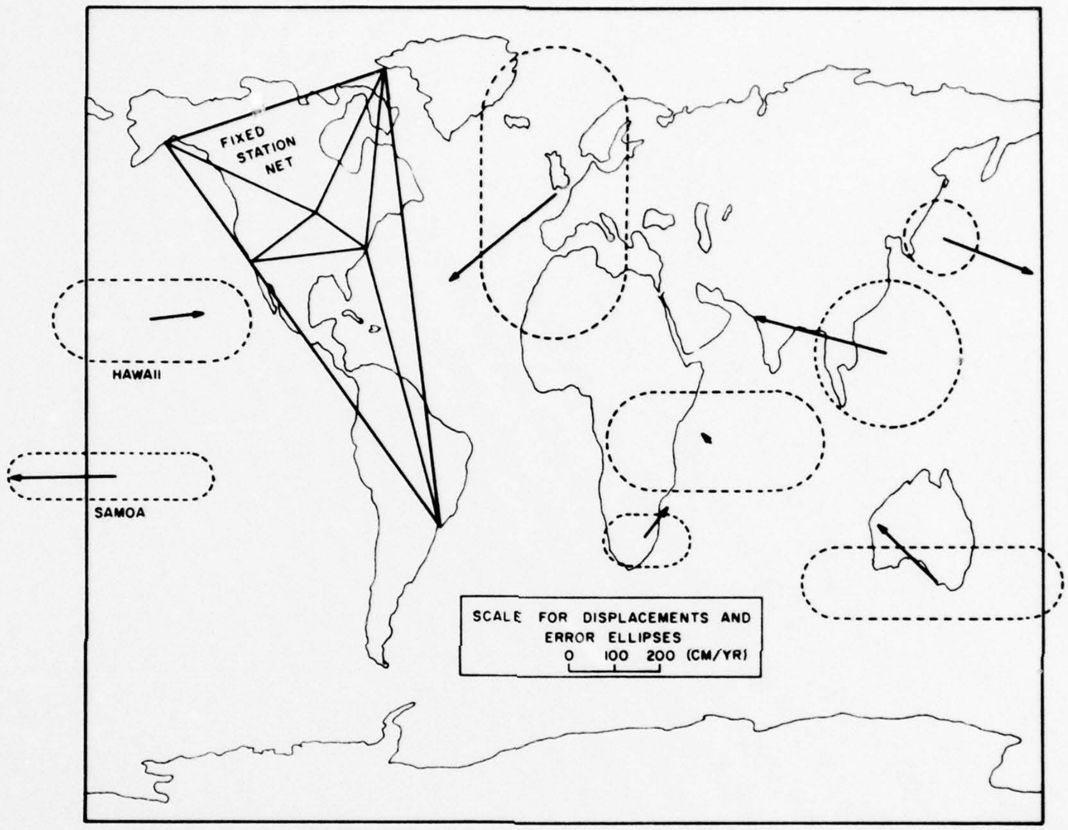

Figure 2. Results of Least Squares Solutions

APPENDIX B

FIGURES

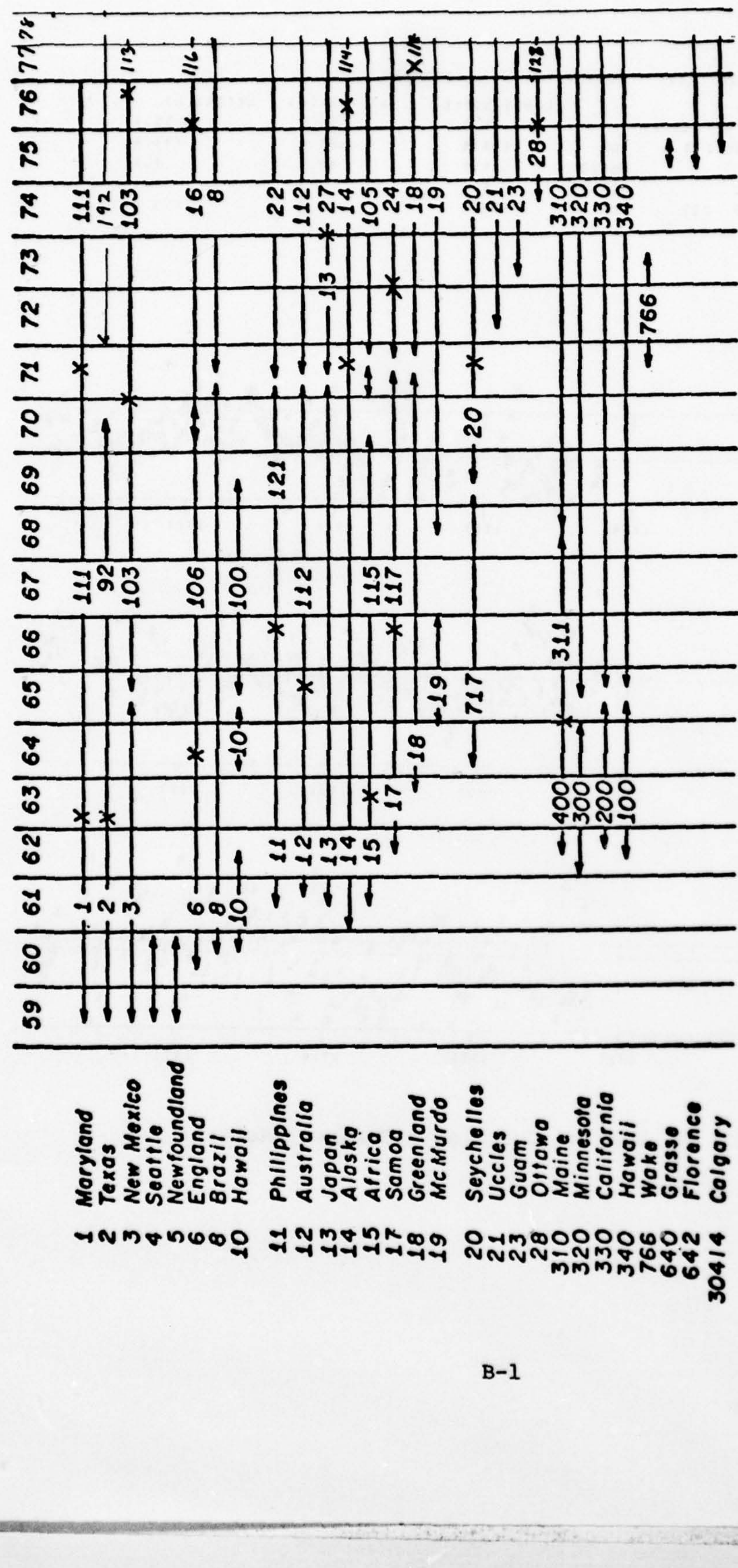

Figure 1. Periods of Operation of Doppler Stations

STATION 311 RESIDUALS (MAINE)

		LONGITUDE(L)	LATITUDE(F)	HEIGHT(H)
AVERAGE NUMBER OF PASSES		16.7	16.7	16.7
RESIDUALS BEFORE FIT	CM	110.4	105.6	148.0
DRIFT	CM/YR	4.5	45.0	5.5
PROBABLE ERROR	CM/YR	4.2	3.1	4.1
RESIDUALS AFTER FIT	CM	104.5	78.2	104.0

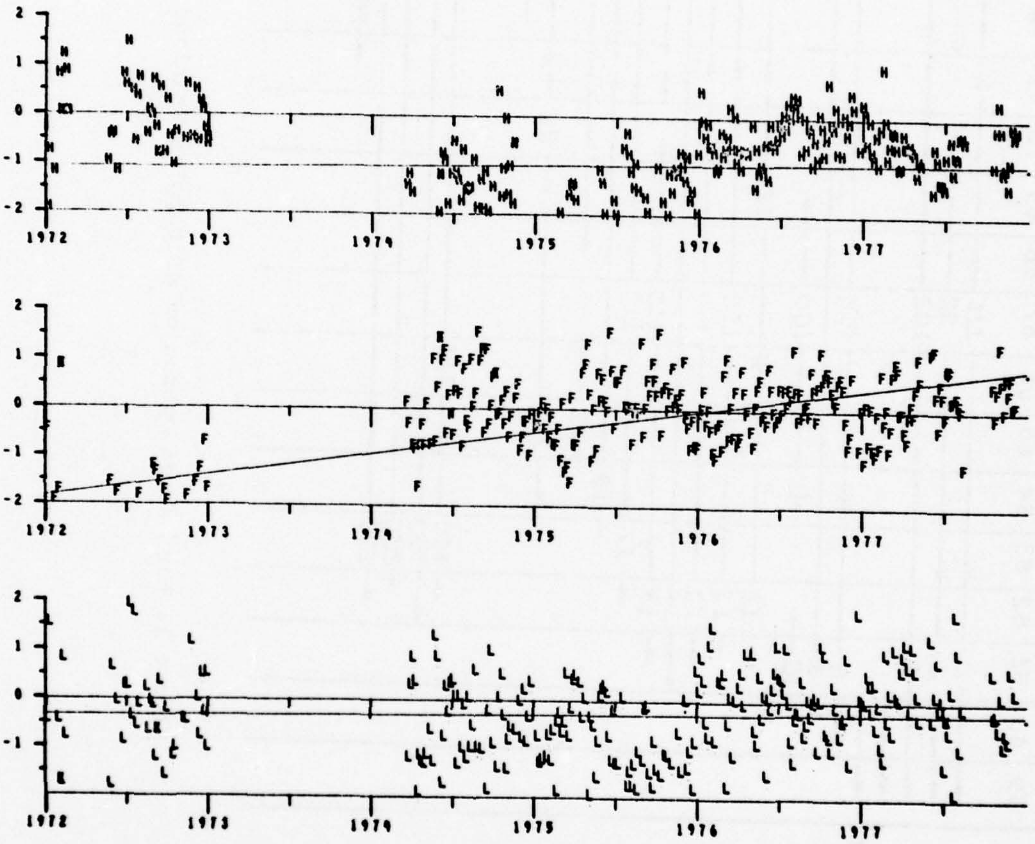

Figure 2a. Station Coordinate Changes (Maine)

STATION 327 RESIDUALS (MINNESOTA)

		LONGITUDE(L)	LATITUDE(F)	HEIGHT(H)
AVERAGE NUMBER OF PASSES		11.1	11.1	11.1
RESIDUALS BEFORE FIT	CM	124.8	63.1	105.7
DRIFT	CM/YR	-41.0	-6.6	-37.1
PROBABLE ERROR	CM/YR	3.4	2.2	3.1
RESIDUALS AFTER FIT	CM	107.6	61.3	84.6

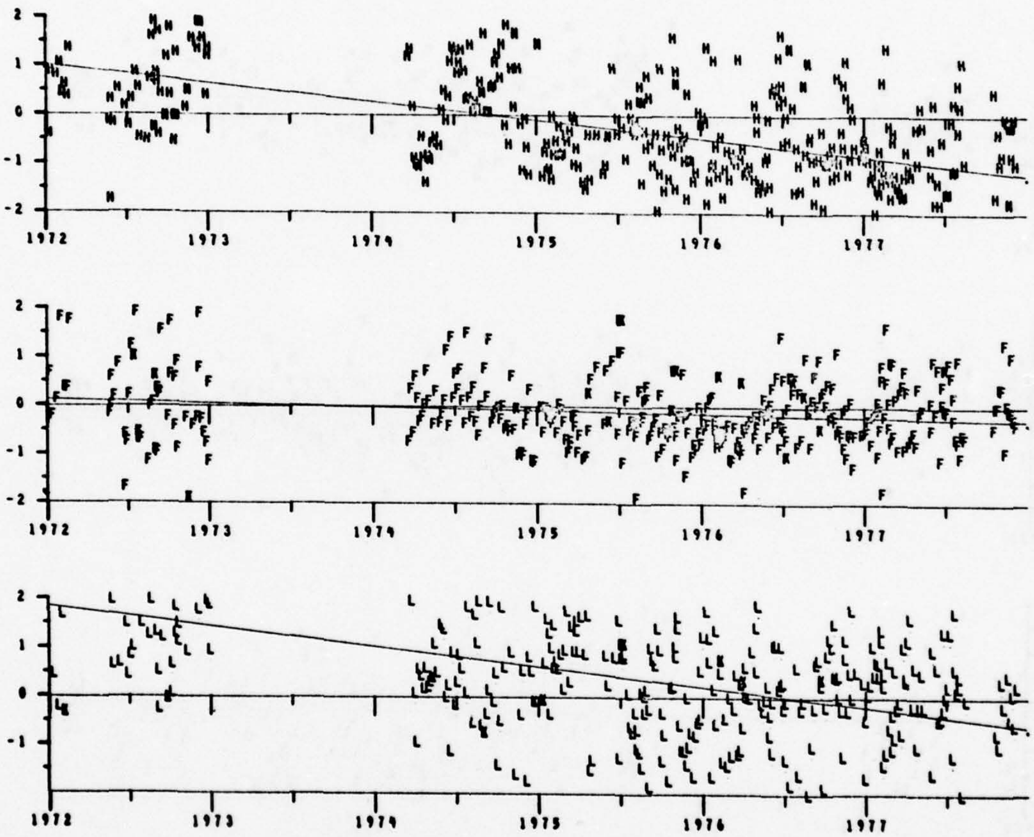

Figure 2b. Station Coordinate Changes (Minnesota)

STATION 334 RESIDUALS (CALIFORNIA)

		LONGITUDE(L)	LATITUDE(F)	HEIGHT(H)
AVERAGE NUMBER OF PASSES		11.4	11.4	11.4
RESIDUALS BEFORE FIT	CM	92.8	51.7	63.7
DRIFT	CM/YR	6.0	-7.5	16.6
PROBABLE ERROR	CM/YR	3.5	2.0	2.2
RESIDUALS AFTER FIT	CM	89.6	50.5	59.4

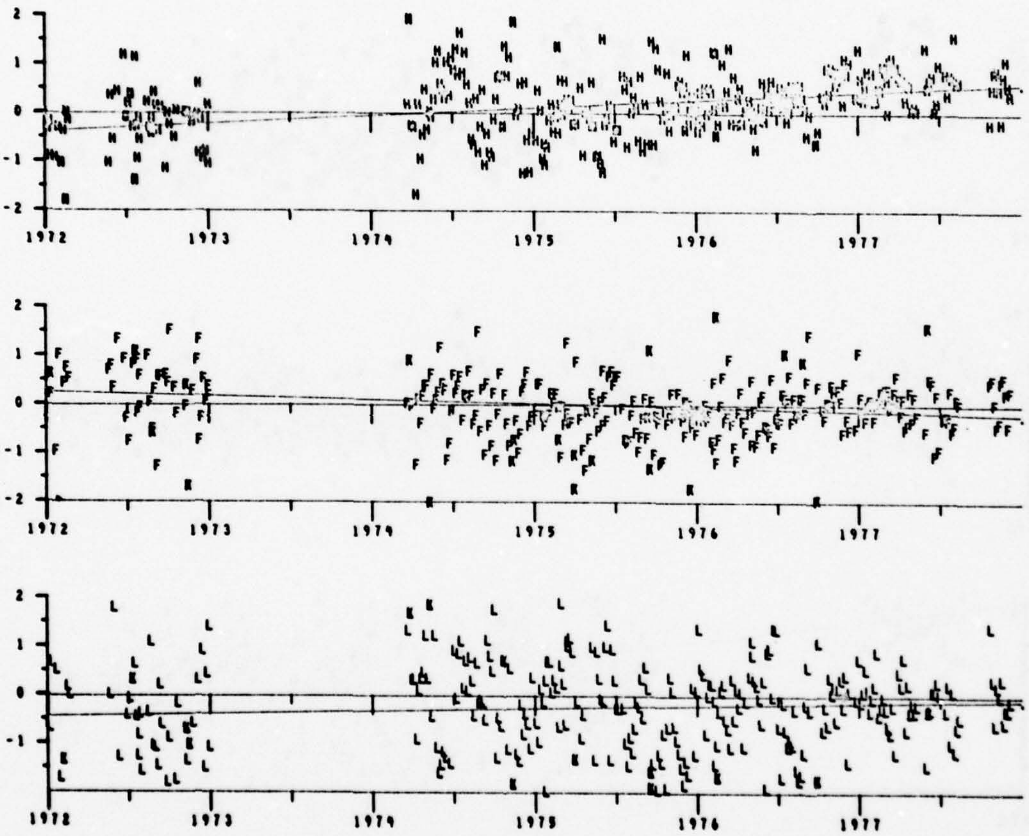

Figure 2c. Station Coordinate Changes (California)

STATION 113 RESIDUALS (NEW MEXICO)

		LONGITUDE(L)	LATITUDE(F)	HEIGHT(H)
AVERAGE NUMBER OF PASSES		14.7	14.7	14.7
RESIDUALS BEFORE FIT	CM	87.4	63.6	93.4
DRIFT	CM/YR	15.1	-0.3	-1.3
PROBABLE ERROR	CM/YR	3.0	2.2	3.3
RESIDUALS AFTER FIT	CM	84.2	62.3	93.3

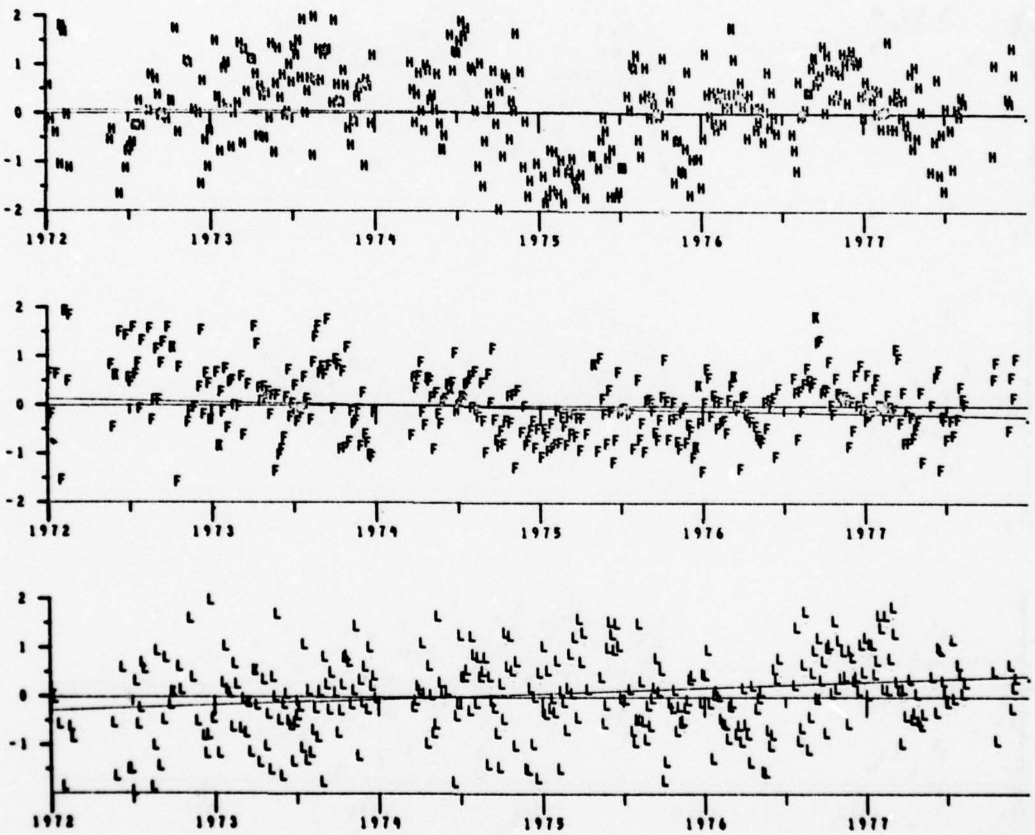

Figure 2d. Station Coordinate Changes (New Mexico)

STATION 111 RESIDUALS (MARYLAND)		LONGITUDE(L)	LATITUDE(F)	HEIGHT(H)
AVERAGE NUMBER OF PASSES		14.6	14.6	14.6
RESIDUALS BEFORE FIT	CM	98.6	56.9	131.9
DRIFT	CM/YR	-14.0	0.0	-47.6
PROBABLE ERROR	CM/YR	4.7	2.8	4.8
RESIDUALS AFTER FIT	CM	91.4	54.7	93.1

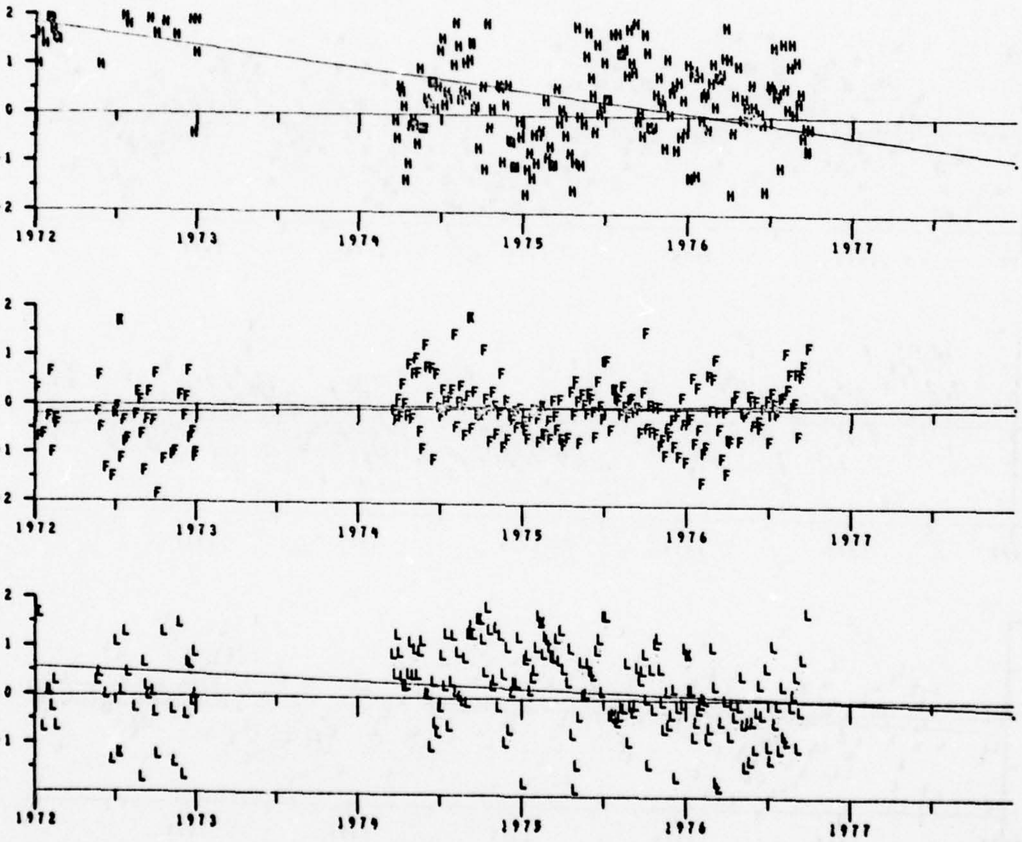

Figure 2e. Station Coordinate Changes (Maryland)

STATION 192 RESIDUALS (TEXAS)

		LONGITUDE(L)	LATITUDE(F)	HEIGHT(H)
AVERAGE NUMBER OF PASSES		11.7	11.7	11.7
RESIDUALS BEFORE FIT	CM	117.6	63.2	121.4
DRIFT	CM/YR	-29.3	-0.8	-26.3
PROBABLE ERROR	CM/YR	6.3	9.2	6.5
RESIDUALS AFTER FIT	CM	93.9	61.9	96.1

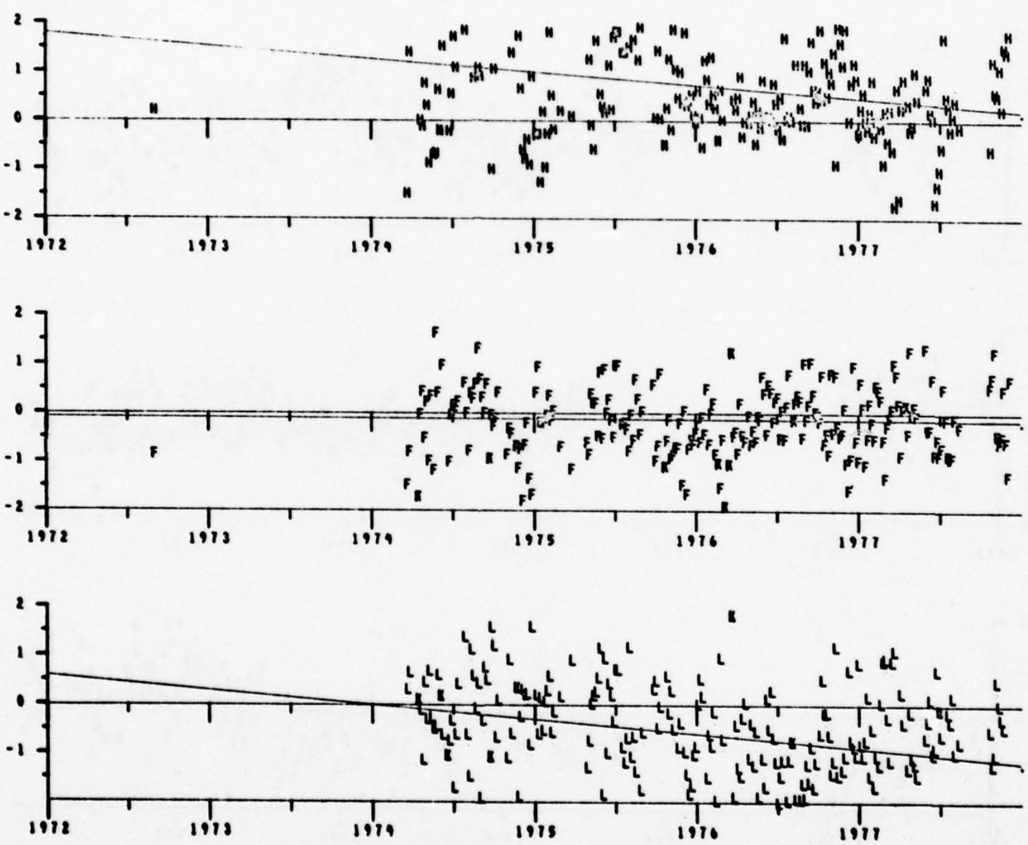

Figure 2f. Station Coordinate Changes (Texas)

STATION 119 RESIDUALS (ALASKA)

		LONGITUDE(L)	LATITUDE(F)	HEIGHT(H)
AVERAGE NUMBER OF PASSES		27.0	27.0	27.0
RESIDUALS BEFORE FIT	CM	92.0	45.0	79.2
DRIFT	CM/YR	27.8	-20.1	5.9
PROBABLE ERROR	CM/YR	4.6	2.3	4.4
RESIDUALS AFTER FIT	CM	76.9	37.6	72.9

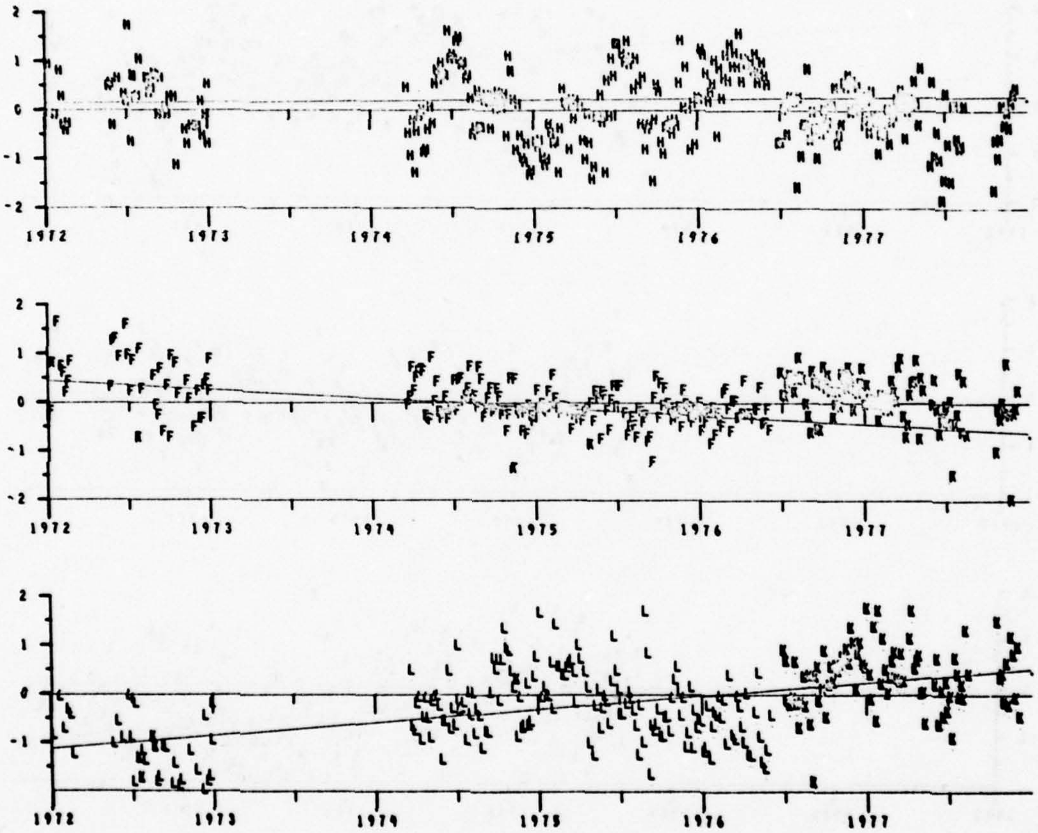

Figure 2g. Station Coordinate Changes (Alaska)

STATION 110 RESIDUALS (GREENLAND)

		LONGITUDE(L)	LATITUDE(F)	HEIGHT(H)
AVERAGE NUMBER OF PASSES		35.5	35.5	35.5
RESIDUALS BEFORE FIT	CM	65.6	56.3	88.1
DRIFT	CM/YR	-10.7	23.3	-4.0
PROBABLE ERROR	CM/YR	2.3	1.9	3.5
RESIDUALS AFTER FIT	CM	54.2	43.8	82.1

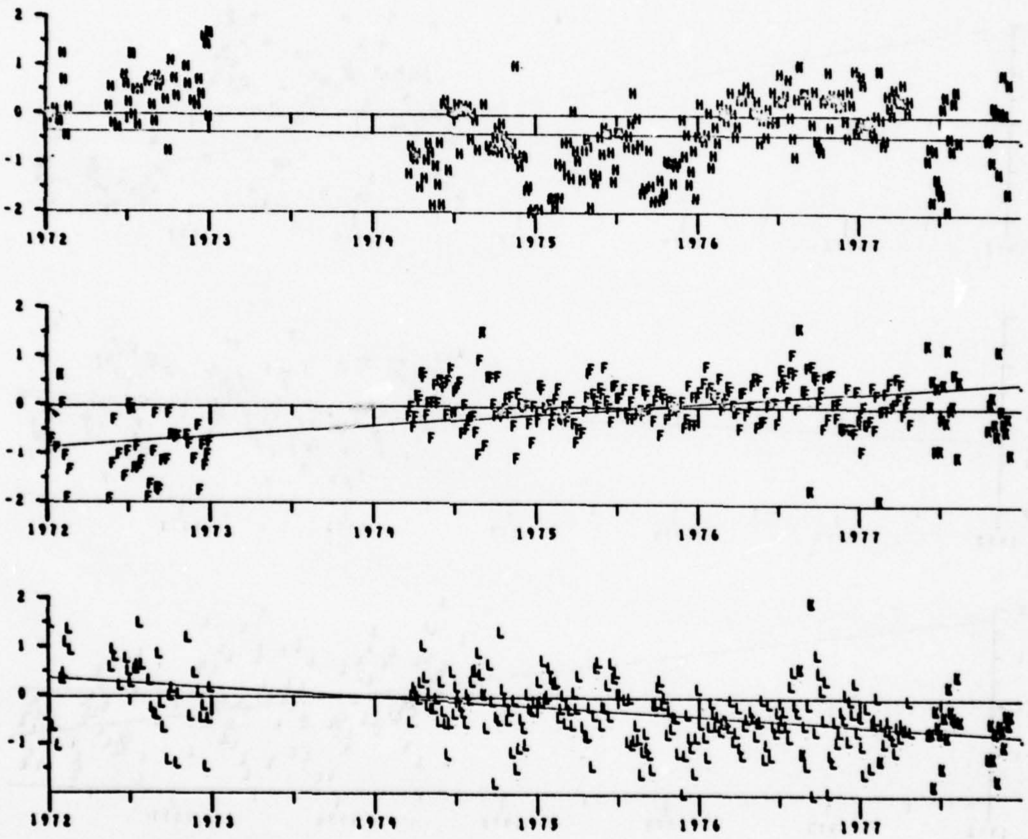

Figure 2h. Station Coordinate Changes (Greenland)

STATION 120 RESIDUALS (OTTAWA)

		LONGITUDE(L)	LATITUDE(F)	HEIGHT(H)
AVERAGE NUMBER OF PASSES		10.7	10.7	10.7
RESIDUALS BEFORE FIT	CM	119.2	73.3	141.0
DRIFT	CM/YR	-45.8	11.8	-91.3
PROBABLE ERROR	CM/YR	11.9	8.1	12.9
RESIDUALS AFTER FIT	CM	108.2	72.7	116.0

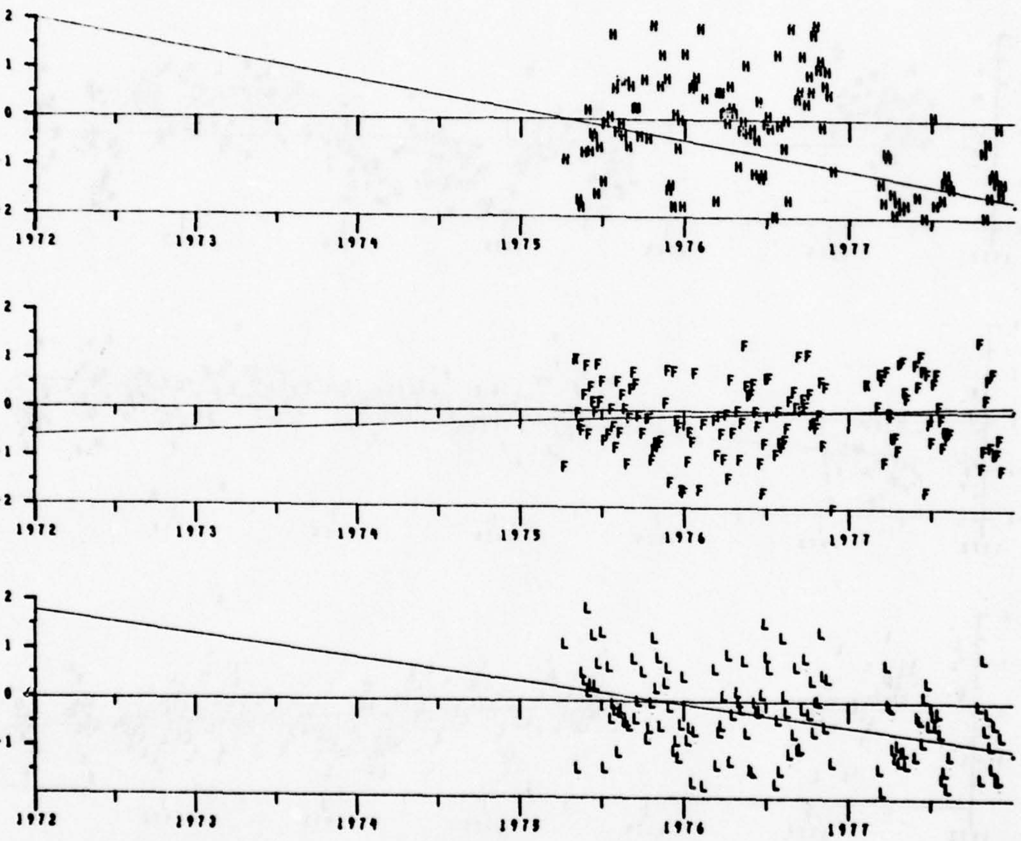

Figure 2i. Station Coordinate Changes (Ottawa)

STATION 30919 RESIDUALS (CALGARY)

		LONGITUDE(L)	LATITUDE(F)	HEIGHT(H)
AVERAGE NUMBER OF PASSES		13.9	13.9	13.9
RESIDUALS BEFORE FIT	CM	97.9	102.8	98.8
DRIFT	CM/YR	-7.9	30.8	69.1
PROBABLE ERROR	CM/YR	9.7	5.5	7.8
RESIDUALS AFTER FIT	CM	97.2	55.2	77.1

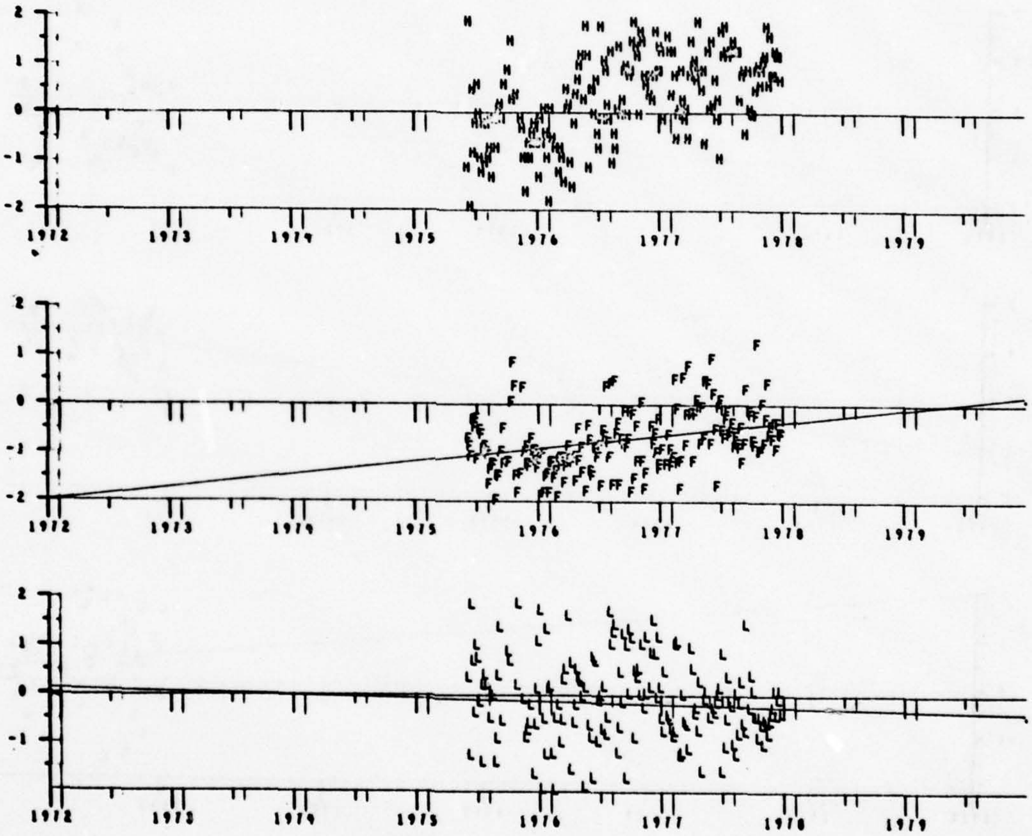

Figure 2j. Station Coordinate Changes (Calgary)

STATION 107 RESIDUALS (VIRGINIA)

		LONGITUDE(L)	LATITUDE(F)	HEIGHT(H)
AVERAGE NUMBER OF PASSES		14.8	14.8	14.8
RESIDUALS BEFORE FIT	CM	90.4	137.2	89.3
DRIFT	CM/YR	-37.0	41.8	17.7
PROBABLE ERROR	CM/YR	37.2	36.0	35.0
RESIDUALS AFTER FIT	CM	76.3	73.9	72.0

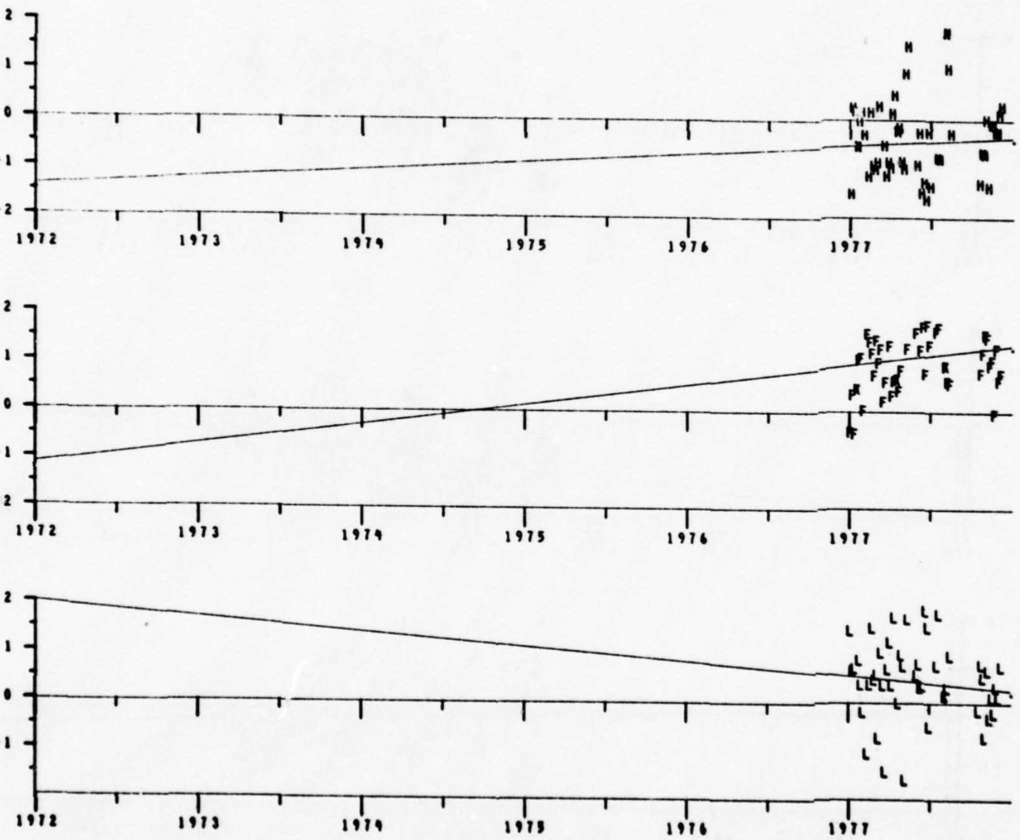

Figure 2k. Station Coordinate Changes (Virginia)

STATION 8 RESIDUALS (BRAZIL)

		LONGITUDE(L)	LATITUDE(F)	HEIGHT(H)
AVERAGE NUMBER OF PASSES		12.0	12.0	12.0
RESIDUALS BEFORE FIT	CM	99.9	77.2	115.5
DRIFT	CM/YR	-5.9	-2.6	-15.1
PROBABLE ERROR	CM/YR	3.7	3.0	3.0
RESIDUALS AFTER FIT	CM	97.0	77.1	98.9

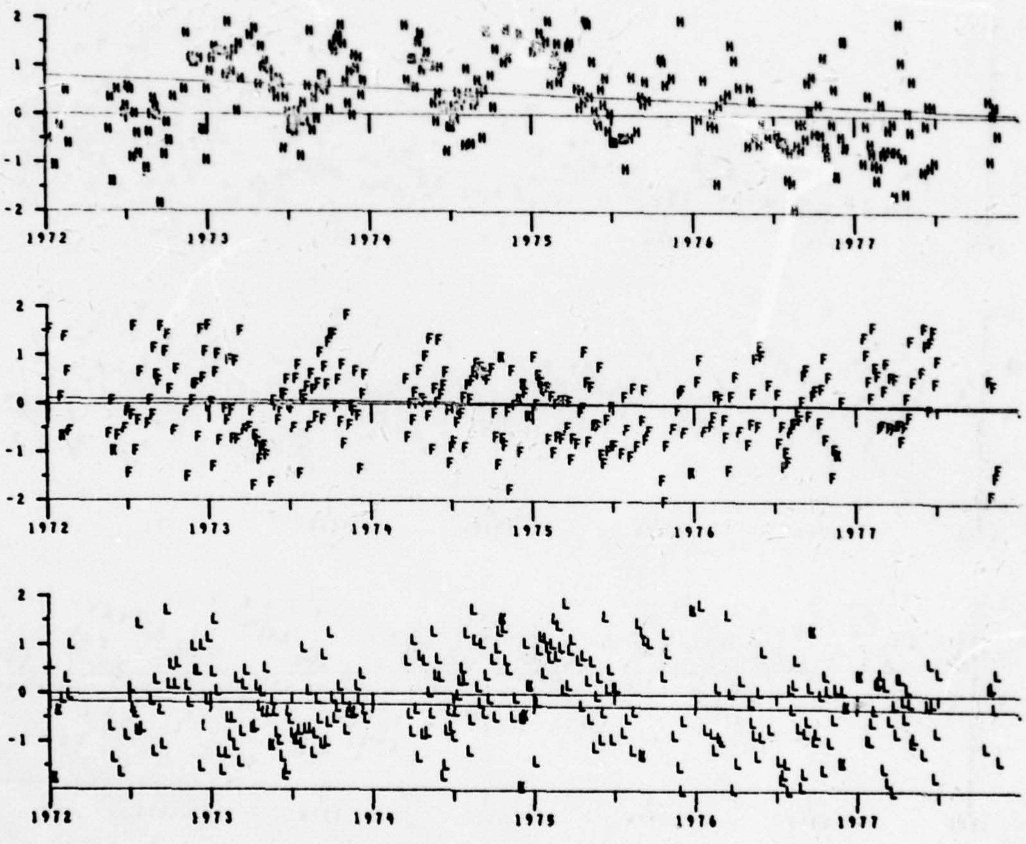

Figure 2L. Station Coordinate Changes (Brazil)

STATION 116 RESIDUALS (ENGLAND)

		LONGITUDE(L)	LATITUDE(F)	HEIGHT(H)
AVERAGE NUMBER OF PASSES		15.6	15.6	15.6
RESIDUALS BEFORE FIT	CM	97.3	56.2	197.1
DRIFT	CM/YR	-0.7	0.9	34.6
PROBABLE ERROR	CM/YR	2.6	2.0	3.0
RESIDUALS AFTER FIT	CM	81.7	56.2	86.0

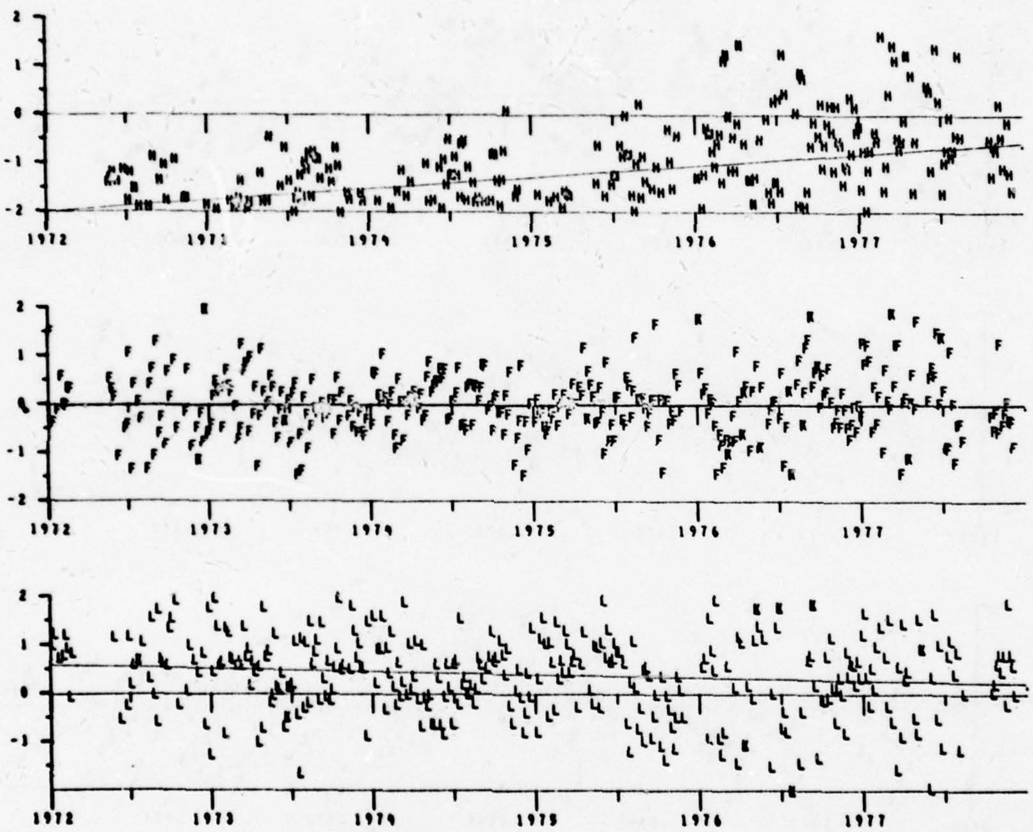

Figure 2m. Station Coordinate Changes (England)

STATION 21 RESIDUALS (BELGIUM)

		LONGITUDE(L)	LATITUDE(F)	HEIGHT(H)
AVERAGE NUMBER OF PASSES		19.3	19.3	19.3
RESIDUALS BEFORE FIT	CM	83.6	57.5	78.6
DRIFT	CM/YR	-25.9	8.3	20.6
PROBABLE ERROR	CM/YR	2.6	2.0	2.5
RESIDUALS AFTER FIT	CM	71.3	55.1	66.3

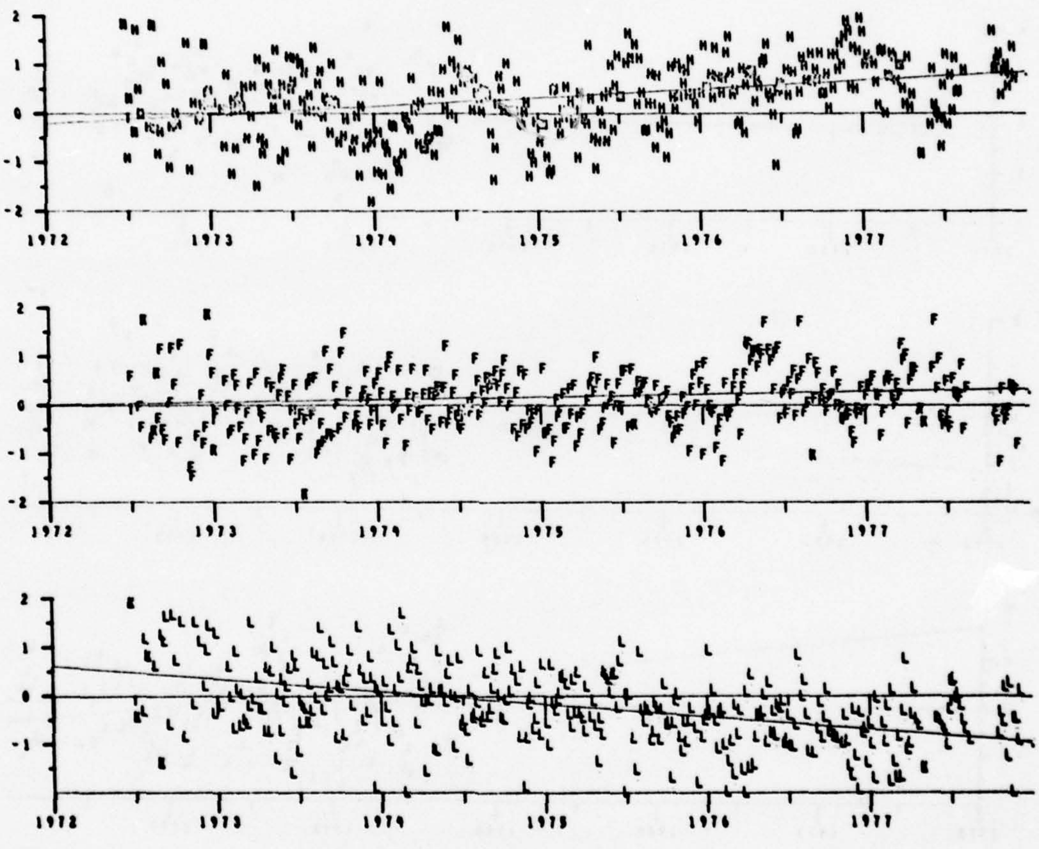

Figure 2n. Station Coordinate Changes (Belgium)

STATION 691 RESIDUALS (FLORENCE)

		LONGITUDE(L)	LATITUDE(F)	HEIGHT(H)
AVERAGE NUMBER OF PASSES		11.0	11.0	11.0
RESIDUALS BEFORE FIT	CM	97.3	65.8	69.2
DRIFT	CM/YR	-35.1	26.2	13.3
PROBABLE ERROR	CM/YR	10.5	7.1	6.3
RESIDUALS AFTER FIT	CM	93.6	62.9	55.1

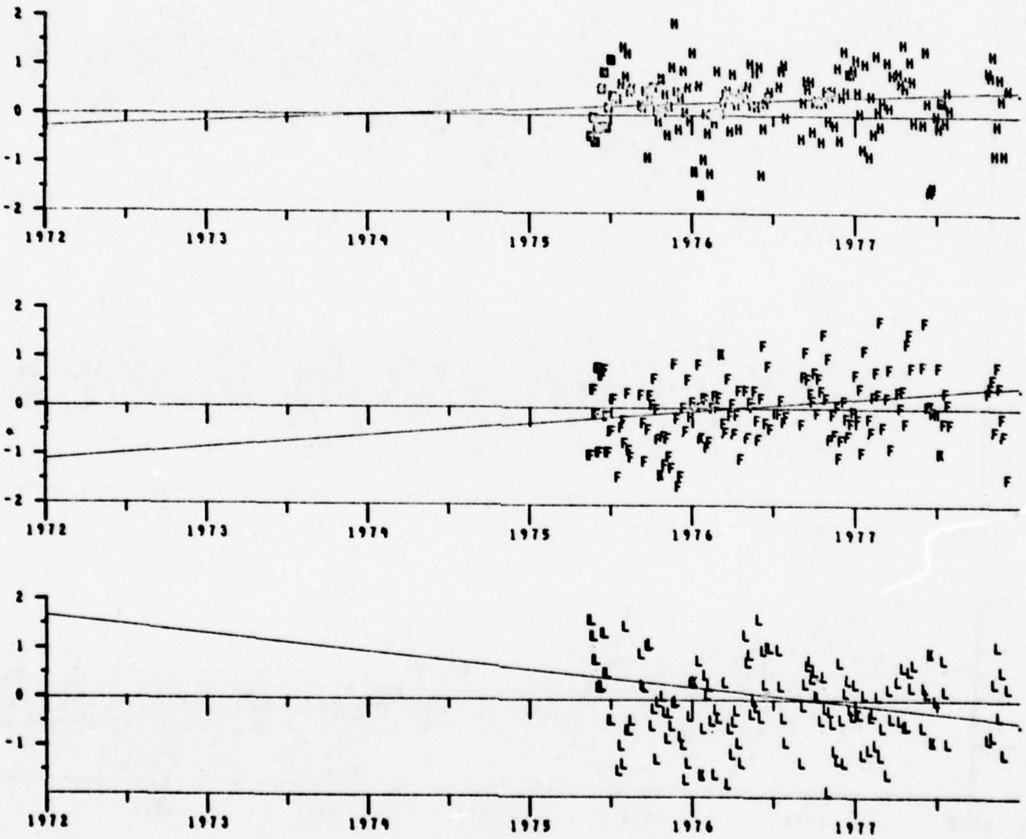

Figure 2o. Station Coordinate Changes (Florence)

STATION 105 RESIDUALS (SO.AFRICA)

		LONGITUDE(L)	LATITUDE(F)	HEIGHT(H)
AVERAGE NUMBER OF PASSES		13.0	13.0	13.0
RESIDUALS BEFORE FIT	CM	101.2	65.5	109.6
DRIFT	CM/YR	-7.1	-1.9	-10.9
PROBABLE ERROR	CM/YR	3.3	2.2	3.3
RESIDUALS AFTER FIT	CM	97.9	69.9	97.1

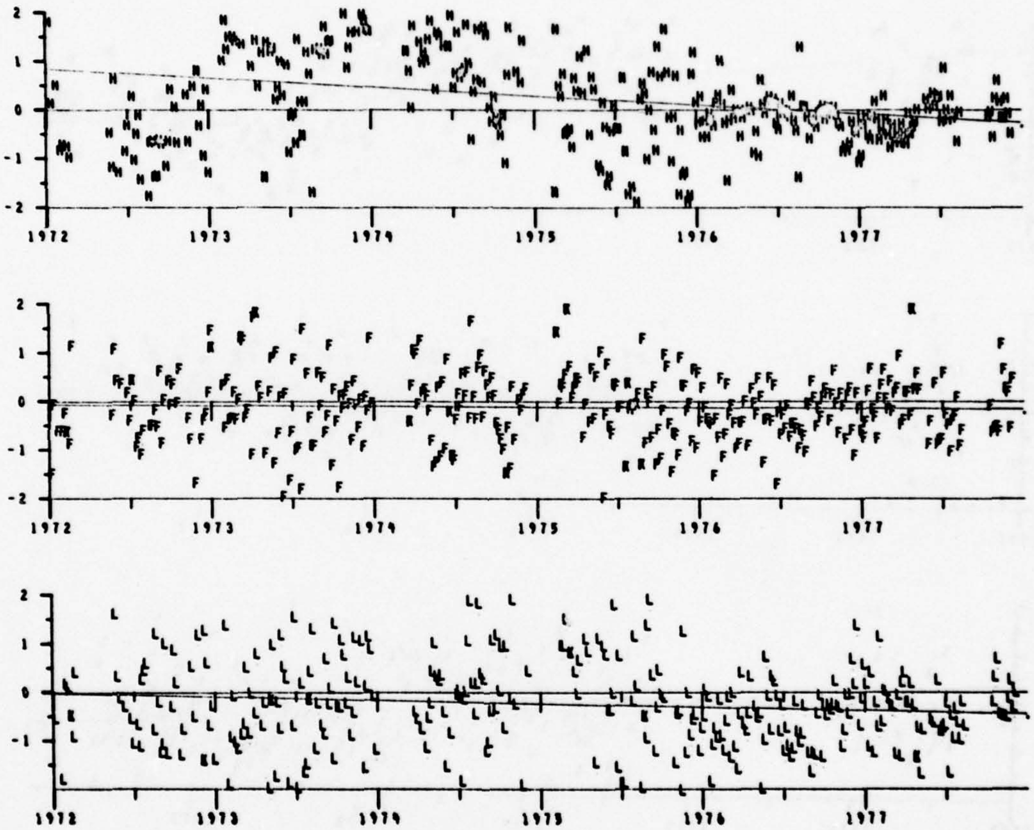

Figure 2p. Station Coordinate Changes (So. Africa)

STATION 20 RESIDUALS (SEYCHELLES)		LONGITUDE(L)	LATITUDE(F)	HEIGHT(H)
AVERAGE NUMBER OF PASSES		11.0	11.0	11.0
RESIDUALS BEFORE FIT	CM	107.4	64.9	97.4
DRIFT	CM/YR	-17.5	3.5	-30.4
PROBABLE ERROR	CM/YR	4.0	2.6	3.0
RESIDUALS AFTER FIT	CM	101.3	64.1	75.3

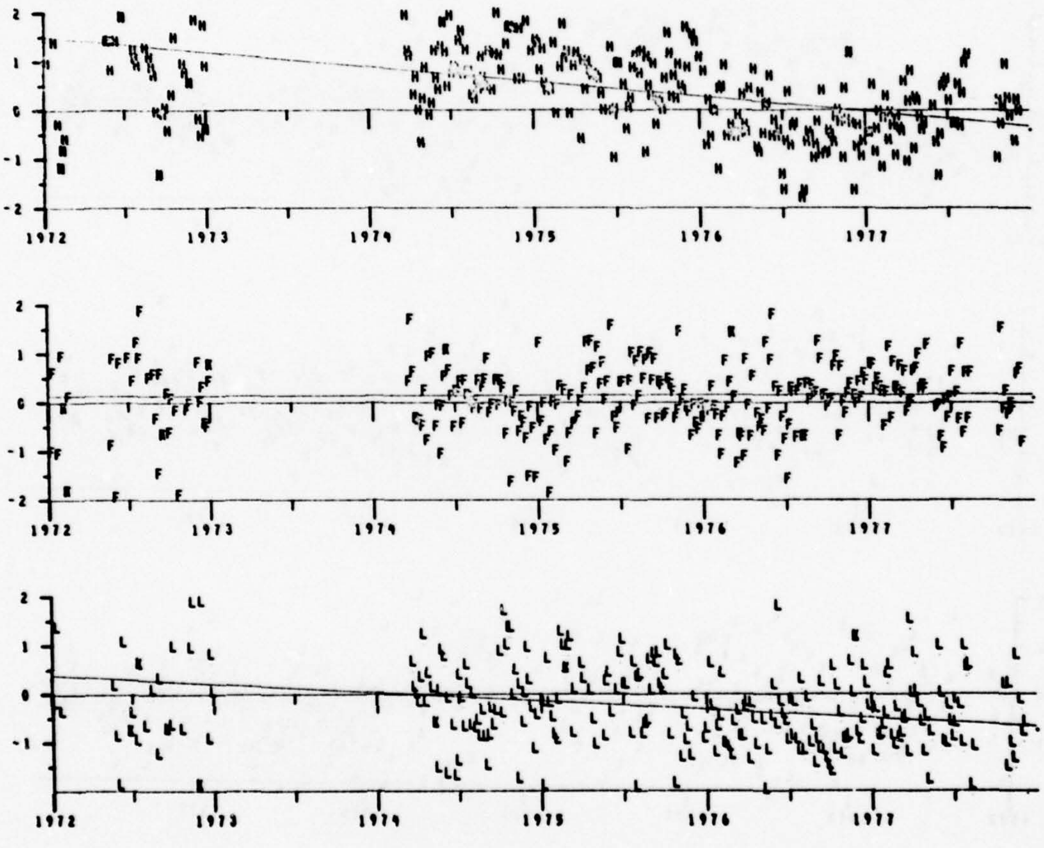

Figure 2q. Station Coordinate Changes (Seychelles)

STATION 27 RESIDUALS (JAPAN)

		LONGITUDE(L)	LATITUDE(F)	HEIGHT(H)
AVERAGE NUMBER OF PASSES		14.8	14.8	14.8
RESIDUALS BEFORE FIT	CM	100.4	92.6	109.4
DRIFT	CM/YR	-19.4	-11.4	25.3
PROBABLE ERROR	CM/YR	3.2	3.1	3.4
RESIDUALS AFTER FIT	CM	95.6	90.1	101.1

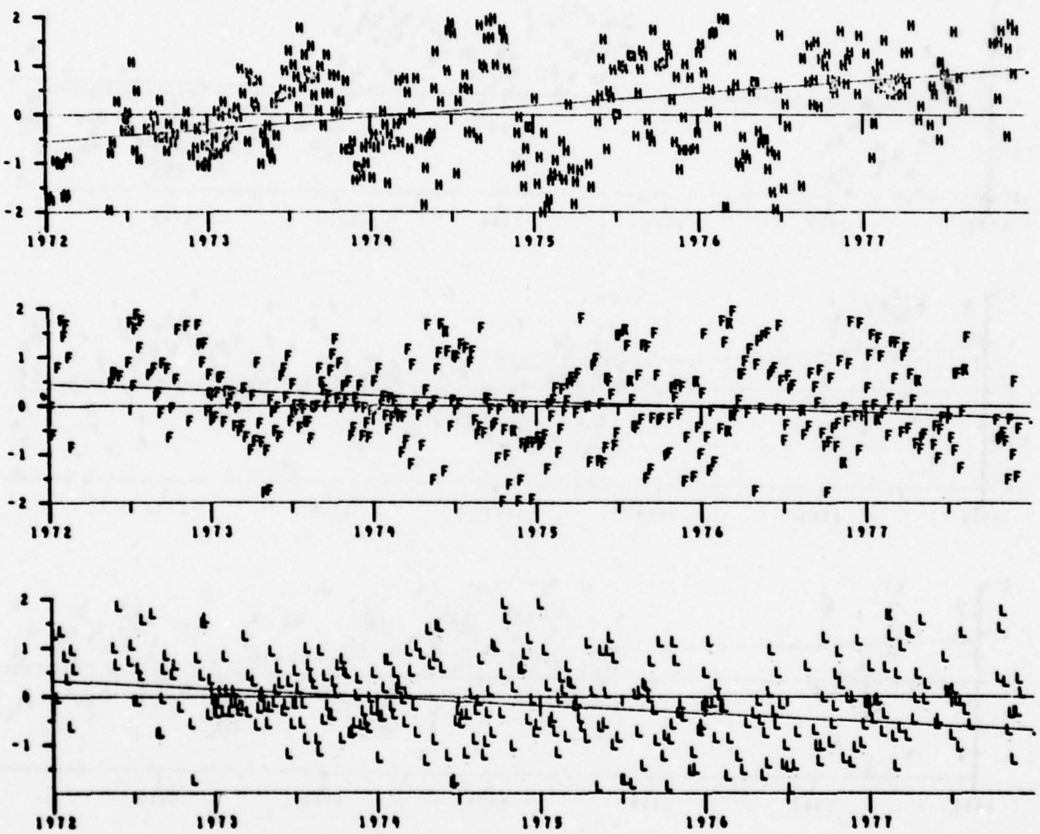

Figure 2r. Station Coordinate Changes (Japan)

STATION 22 RESIDUALS (PHILLIPINES)

		LONGITUDE(L)	LATITUDE(F)	HEIGHT(H)
AVERAGE NUMBER OF PASSES		12.1	12.1	12.1
RESIDUALS BEFORE FIT	CM	118.3	96.6	151.0
DRIFT	CM/YR	-15.4	-18.9	10.3
PROBABLE ERROR	CM/YR	4.2	3.5	6.0
RESIDUALS AFTER FIT	CM	106.0	88.1	150.2

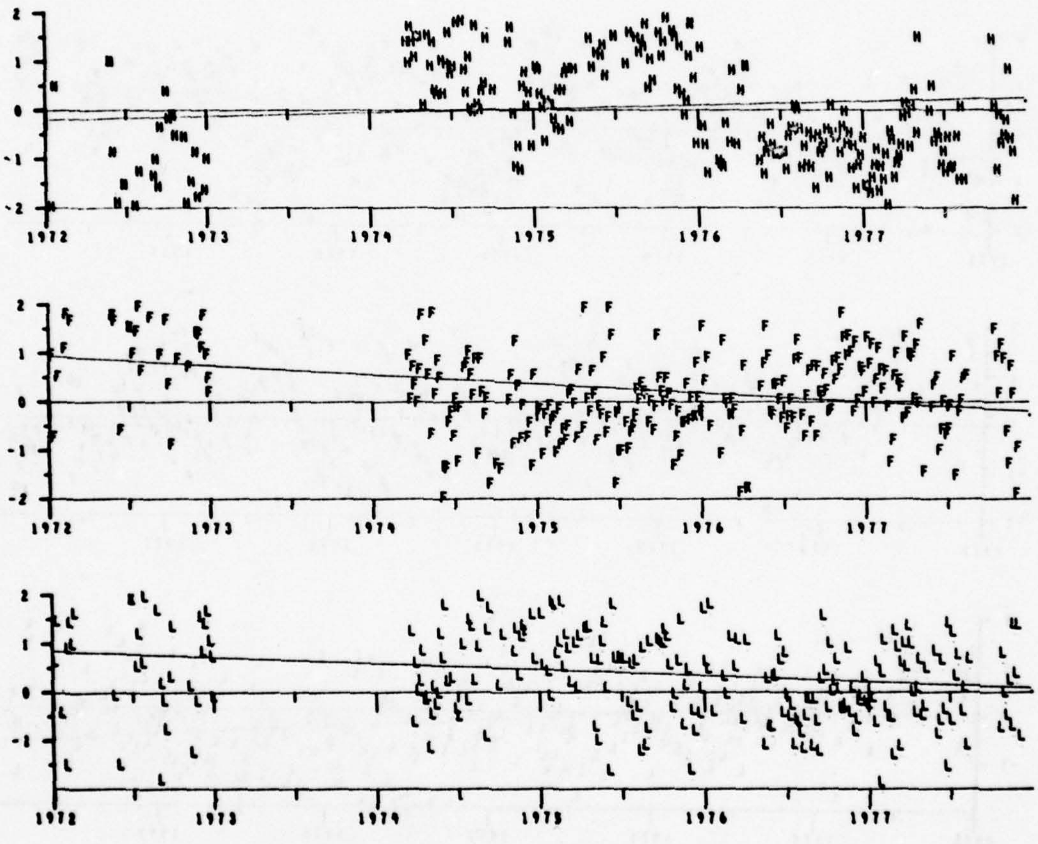

Figure 2s. Station Coordinate Changes (Phillipines)

STATION 340 RESIDUALS (HAWAII)

		LONGITUDE(L)	LATITUDE(F)	HEIGHT(H)
AVERAGE NUMBER OF PASSES		12.4	12.4	12.4
RESIDUALS BEFORE FIT	CM	100.1	67.1	85.9
DRIFT	CM/YR	-3.3	-1.0	7.4
PROBABLE ERROR	CM/YR	4.2	2.6	3.0
RESIDUALS AFTER FIT	CM	107.0	67.0	75.1

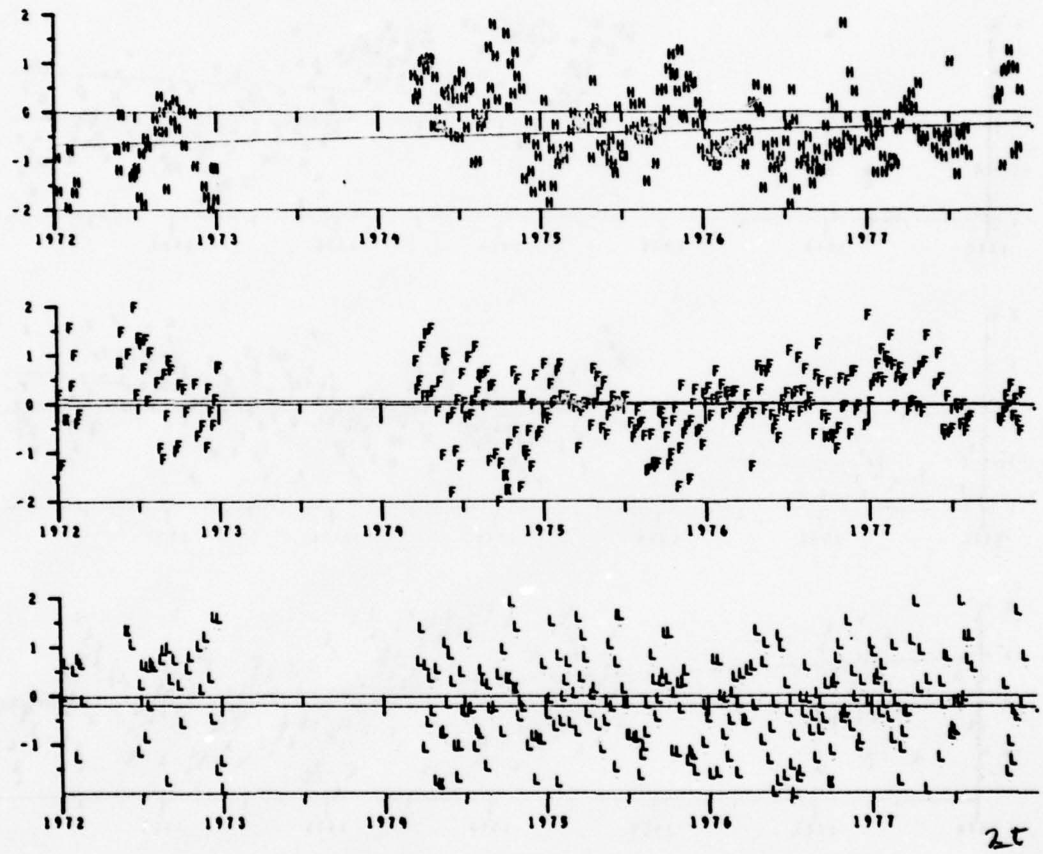

Figure 2t. Station Coordinate Changes (Hawaii)

STATION 24 RESIDUALS (SAMOA)

		LONGITUDE(L)	LATITUDE(F)	HEIGHT(H)
AVERAGE NUMBER OF PASSES		13.0	13.0	13.0
RESIDUALS BEFORE FIT	CM	114.2	102.5	176.2
DRIFT	CM/YR	-18.2	40.2	18.3
PROBABLE ERROR	CM/YR	4.3	3.4	6.8
RESIDUALS AFTER FIT	CM	106.2	82.2	165.4

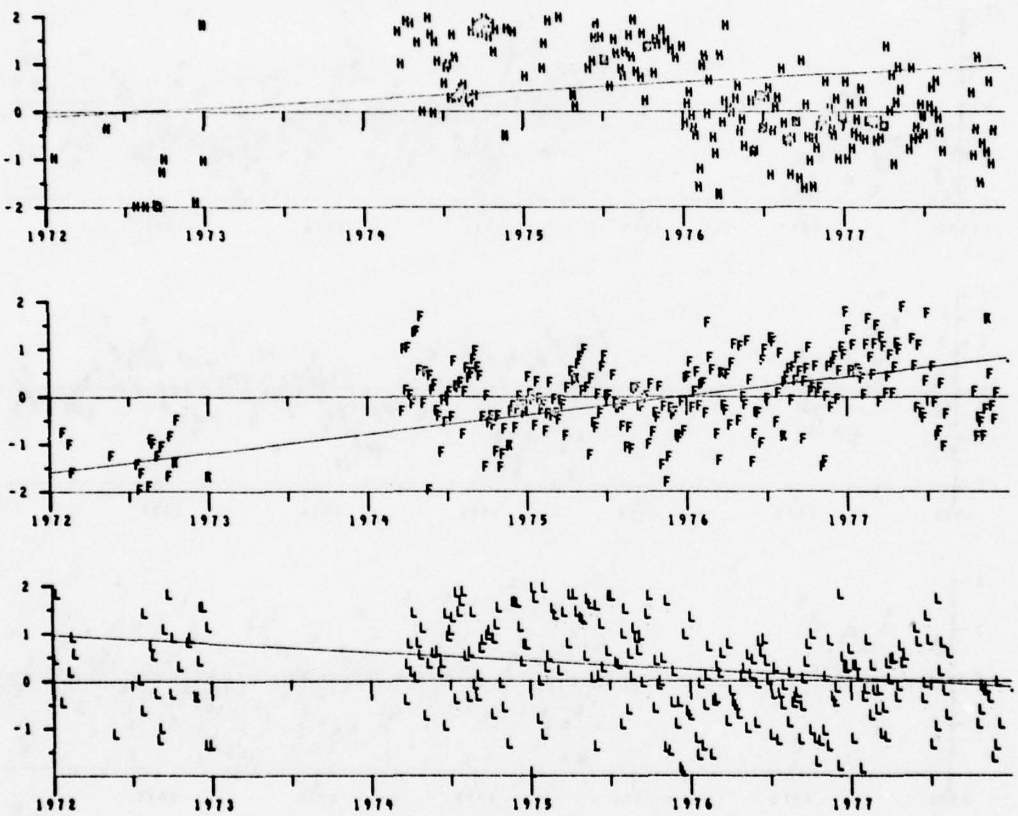

Figure 2u. Station Coordinate Changes (Samoa)

STATION 23 RESIDUALS (GUAM)

		LONGITUDE(L)	LATITUDE(F)	HEIGHT(H)
AVERAGE NUMBER OF PASSES		11.6	11.6	11.6
RESIDUALS BEFORE FIT	CM	107.9	63.9	192.9
DRIFT	CM/YR	-33.9	1.8	-55.2
PROBABLE ERROR	CM/YR	6.0	9.2	6.6
RESIDUALS AFTER FIT	CM	92.1	63.7	98.9

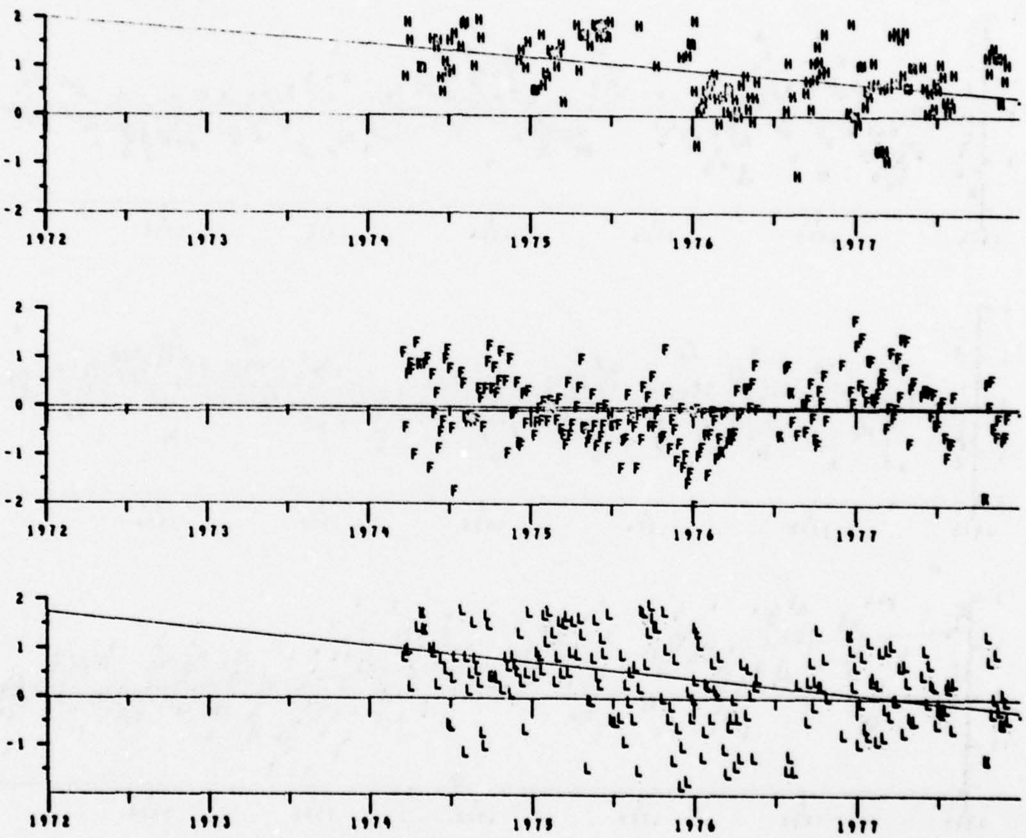

Figure 2v. Station Coordinate Changes (Guam)

STATION 112 RESIDUALS (AUSTRALIA)

		LONGITUDE(L)	LATITUDE(F)	HEIGHT(H)
AVERAGE NUMBER OF PASSES		16.8	16.8	16.8
RESIDUALS BEFORE FIT	CM	95.9	49.1	52.2
DRIFT	CM/YR	-27.1	12.1	2.7
PROBABLE ERROR	CM/YR	2.9	1.5	1.7
RESIDUALS AFTER FIT	CM	71.7	49.7	50.1

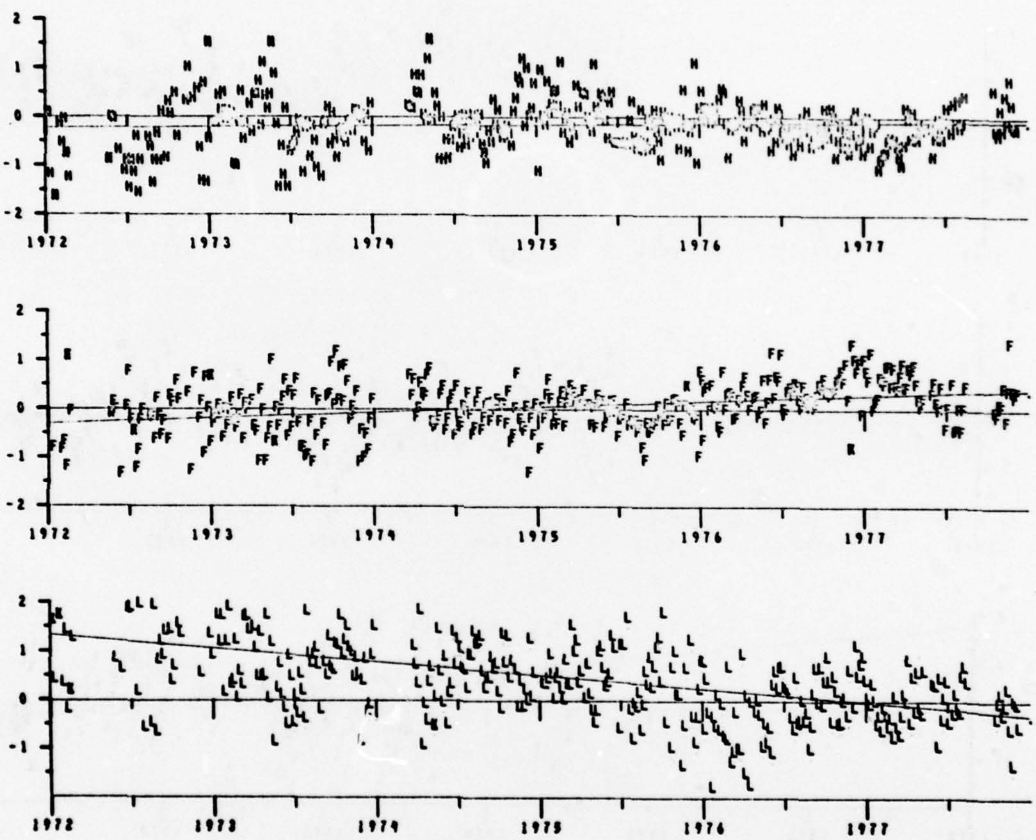

Figure 2w. Station Coordinate Changes (Australia)

STATION 19 RESIDUALS (MCMURDO)

		LONGITUDE(L)	LATITUDE(F)	HEIGHT(H)
AVERAGE NUMBER OF PASSES		17.5	17.5	17.5
RESIDUALS BEFORE FIT	CM	128.7	136.1	209.0
DRIFT	CM/YR	-33.9	-1.2	7.2
PROBABLE ERROR	CM/YR	5.7	6.3	5.8
RESIDUALS AFTER FIT	CM	120.1	131.9	120.2

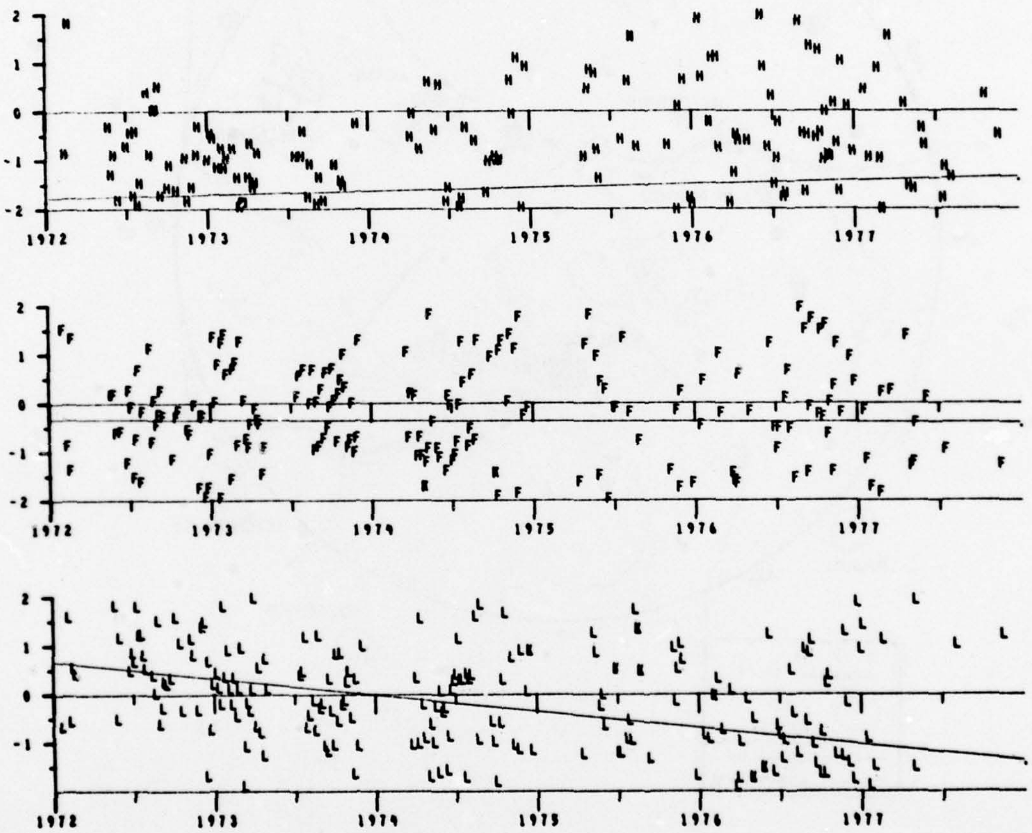

Figure 2x. Station Coordinate Changes (McMurdo)

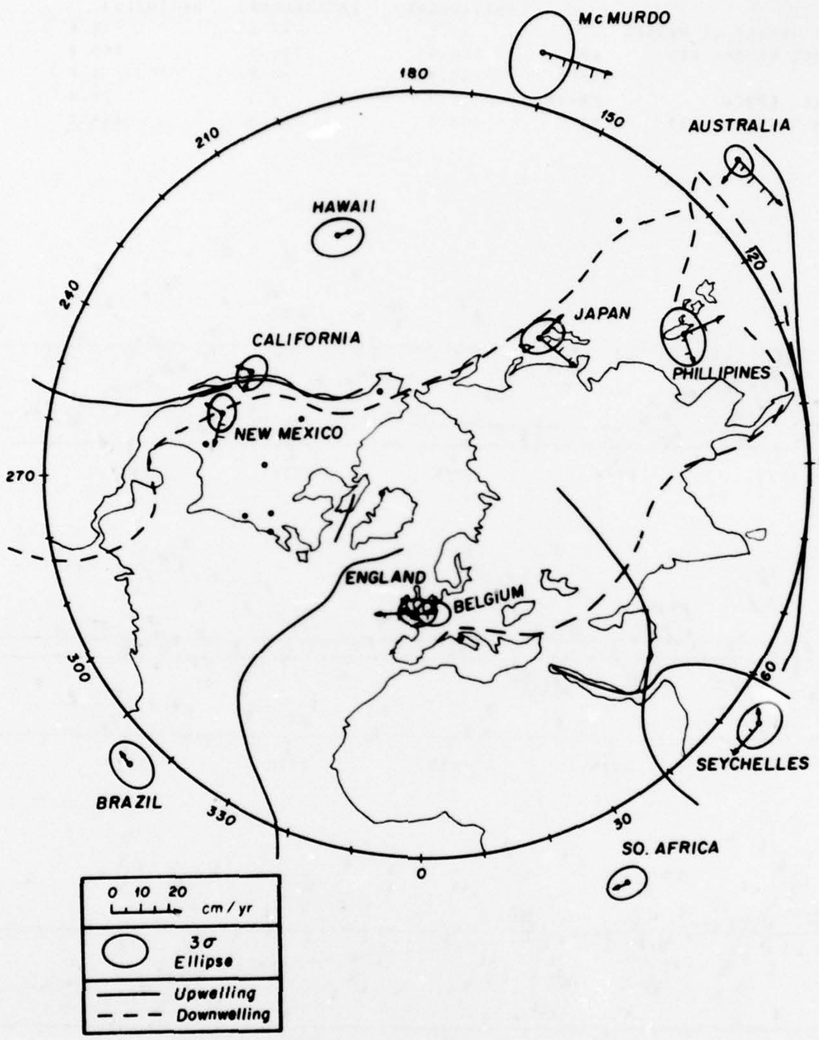

Figure 3. Station Position Changes 1972-1978

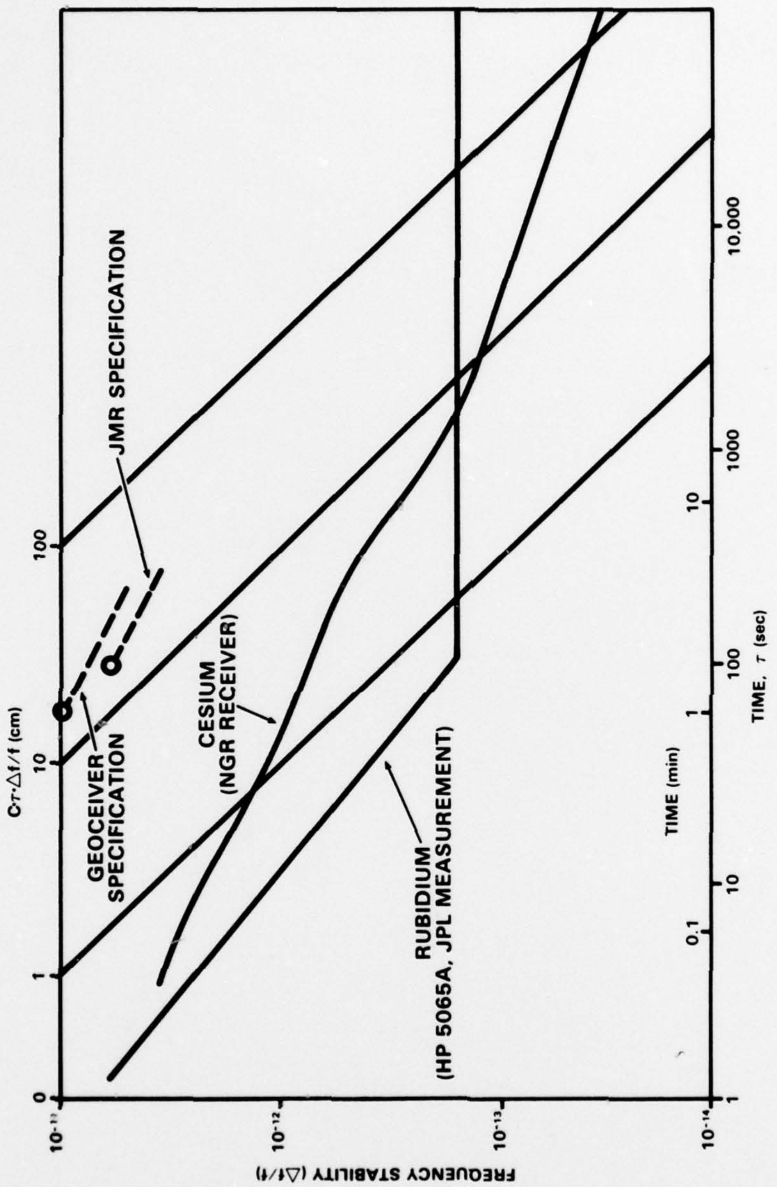

Figure 4. Oscillator Stability

APPENDIX C

TABLES

Table 1. Station Coordinate Changes
Over Six Years (cm/yr)

Station	Longitude	Latitude	Height
North America			
California	6.0±3.5	-7.5±2.0	16.6±2.2
New Mexico	15.1±3.0	-8.3±2.2	-1.3±3.3
South America			
Brazil	-5.4±3.7	-2.6±3.0	-15.1±3.8
Europe			
England	-8.7±2.8	0.9±2.0	34.6±3.0
Belgium	-25.9±2.6	8.3±2.0	20.6±2.5
Africa			
South Africa	-7.1±3.3	-1.4±2.2	-18.4±3.3
Seychelles[1]	-17.5±4.0	3.5±2.6	30.4±3.0
Asia			
Japan	-19.4±3.2	-11.4±3.1	25.3±3.4
Phillipines	-15.4±4.2	-18.9±3.5	10.3±3.0
Pacific			
Hawai[1]	-3.3±4.2	-1.8±2.6	7.4_3.0
Australia			
Adelaide	-27.1±2.4	12.1±1.5	2.7±1.7
Antarctica			
McMurdo	-33.9±5.7	-1.2±6.3	7.2±5.8
RMS	12.5[2],3.6	8.4,3.0	18.8,3.6

[1] Solutions were not computed in 1973.
[2] About mean

Table 2a. Position Change Rates (Longitude, cm/yr)

Station Number	Location	Post 1972.0 Data Processed	Data Omitted	Data Span Limit of Solution: 1973.0 - 1975.5	1972.0 - 1978.0	1972.0 - 1978.0 w/o 1973 - 1975	1964.0 - 1978.0	Post 1972 Station Move
NORTH AMERICA								
311	Maine	1964.0-1978.0	1973	16±10	4.5±4.2	4.5	6.4±1.8	Intermittent (1)
327	Minnesota	1965.0-1978.0	1973	25±33	-41.0±3.9	-42.4	-22.8±2.0	Intermittent
334	California	1964.0-1978.0	1973	-38±26	6.0±3.5	10.3	2.5±1.6	Intermittent
113	New Mexico	1964.0-1978.0	None	16±10	15.1±3.0	20.2	15.3±1.7	1976.5
111	Maryland	1964.0-1976.7	1973	7±21	-14.8±4.7	-18.3	4.4±2.0	
192	Texas	1974.0-1978.0	None	-2±25	-29.3±6.3	23.3	(2)	None
114	Alaska	1964.0-1976.0	1973	47±19	27.8±4.6	13.7	10.1±1.9	1976.0
118	Greenland	1964.0-1977.0	1973	-2±11	-18.7±2.3	-17.2	-10.5±1.1	1977.0
128	Ottawa	1975.3-1978.0	None	N.A.	-45.8±11.9	N.A.	(2)	1977.0
30414	Calgary	1975.4-1978.0	None	N.A.	-7.9±9.7	N.A.	(2)	None
107	Virginia	1976.0-1978.0	None	N.A.	-37.0±37.2	N.A.	(2)	None
SOUTH AMERICA								
8	Brazil	1964.0-1978.0	None	46±9	-5.4±3.7	-8.3	-3.4±2.1	None
EUROPE								
116	England	1971.5-1978.0	None	5±8	-8.7±2.8	-10.3	-8.8±2.8	1976.0
21	Belgium	1972.3-1978.0	None	-5±7	-25.9±2.6	-36.3	(2)	None
641	Italy	1975.0-1978.0	None	N.A.	-35.1±10.5	N.A.	(2)	None
AFRICA								
105	So. Africa	1965.0-1978.0	None	35±15	-7.1±3.3	-5.4	2.4±1.8	None
20	Seychelles	1965.0-1978.0	1973	11±28	-17.5±4.0	-15.3	-8.6±2.1	None
ASIA								
27	Japan	1964.0-1978.0	None	N.A.	-19.4±3.2	-23.5	1.9±1.8	1974.2
22	Phillipines	1964.0-1978.0	None	28±27	-15.4±4.2	-9.3	-6.3±2.0	None
PACIFIC								
340	Hawaii	1964.0-1978.0	1973	-19±31	-3.3±4.2	-2.6	3.8±1.9	None
117	Samoa-1	1964.0-1973.0	1973	62±31	N.A.	N.A.	-6.5±9.2	1973
24	Samoa-2	1974.0-1978.0	1973	N.A.	-38.4±6.2	N.A.	(2)	1973
23	Guam	1974.0-1978.0	None	-16±29	-33.4±6.0	N.A.	(2)	None
AUSTRALIA								
112	Adelaide	1964.0-1978.0	None	-9±7	-27.1±2.4	-29.8	-14.2±1.4	None
ANTARCTIC								
19	McMurdo	1965.6-1978.0	None	4±21	-33.9±5.7	-36.1	-23.7±3.6	None

NOTES: N.A. - Not applicable or not available due to short data span.
(1) - Station was not actually moved but different antennas are used.
(2) - Same as 1972.0-1978.0 because station started operations after 1972.0.

Table 2b. Position Change Rates (Latitude, cm/yr)

Station	Data Processed	Post 1972 Data Omitted	Data Span Limit of Solution: 1973.0 - 1975.5	1972.0 - 1978.0	1972.0 - 1978.0 w/o 1973 - 1975	1964.0 - 1978.0	Post 1972 Station Move
NORTH AMERICA							
Maine	1964.0-1978.0	1973	-16±23	45.0±3.1	54.9	15.9±1.5	Intermittent (1)
Minnesota	1965.0-1978.0	1973	-75±19	-6.6±2.2	-4.7	-5.9±1.3	Intermittent
California	1964.0-1978.0	1973	-25±15	-7.5±2.0	-8.9	-1.3±1.1	Intermittent
New Mexico	1972.0-1978.0	None	-34±7	-8.3±2.2	-13.5	7.0±1.3	1976.5
Maryland	1964.0-1976.7	1973	-29±13	8.8±2.8	10.5	4.4±1.4	
Texas	1974.0-1978.0	None	-12±25	-.8±4.2	0.8	(2)	None
Alaska	1964.0-1976.0	1973	-5±9	-20.1±2.3	-18.8	-9.0±1.2	1976.0
Greenland	1964.0-1977.0	1973	-28±10	23.3±1.9	25.8	6.2±1.1	1977.0
Ottawa	1975.3-1978.0	None	N.A.	11.8±8.1	N.A.	(2)	1977.0
Calgary	1975.0-1976.0	None	N.A.	30.8±5.5	N.A.	(2)	None
Virginia	1976.0-1978.0	None	N.A.	41.8±36.0	N.A.	(2)	None
SOUTH AMERICA							
Brazil	1964.0-1978.0	None	-8±8	-2.6±3.0	-2.6	-7.6±2.0	None
EUROPE							
England	1971.5-1978.0	None	-5±5	.9±2.0	3.2	-0.0±1.9	1976.0
Belgium	1972.3-1978.0	None	8±6	8.3±2.0	1.8	(2)	None
Italy	1975.0-1978.0	None	N.A.	26.2±7.1	N.A.	(2)	None
AFRICA							
South Africa	1965.0-1978.0	None	10±9	-1.4±2.2	1.8	-10.6±1.3	None
Seychelles	1965.0-1978.0	1973	-29±19	3.5±2.6	3.0	0.7±1.6	None
ASIA							
Japan	1964.0-1978.0	None	N.A.	-11.4±3.1	-16.8	0.1±1.6	1974.2
Phillipines	1964.0-1978.0	None	-56±22	-18.9±3.5	-25.0	-7.2±1.7	None
PACIFIC							
Hawaii	1964.0-1978.0	1973	-19±22	-1.8±2.6	-1.5	9.8±1.2	None
Samoa-1	1964.0-1978.0	1973	-32±19	N.A.	N.A.	6.4±6.7	1973.0
Samoa-2	1974. -1978.0	1973	N.A.	13.6±4.4	N.A.	(2)	1973.
Guam	1974. -1978.0	None	-59±18	1.8±4.2	N.A.	(2)	None
AUSTRALIA							
Adelaide	1964.0-1978.0	None	7±5	12.1±1.5	12.8	12.7±1.0	None
ANTARCTIC							
McMurdo	1965.6-1978.0	None	-29±22	-1.2±6.3	3.2	-0.2±3.8	None

NOTES: N.A. - Not applicable or not available due to short data span.
(1) - Station was not actually moved but different antennas are used.
(2) - Same as 1972.0-1978.0 because station started operations after 1972.0.

Table 2c. Position Change Rates (Height, cm/yr)

Station Number	Location	Data Processed	Post 1972 Data Omitted	Data Span Limit of Solution: 1973.0 - 1975.5	1972.0 - 1978.0	1972.0-1978.0 w/o 1973-1975	1964.0 - 1978.0	Post 1972 Station Move
NORTH AMERICA								
311	Maine	1964.0-1978.0	1973	-54±24	5.5±4.1	-10.8	2.9±1.6	Intermittent (1)
327	Minnesota	1965.0-1978.0	1973	-129±26	-37.1±3.1	-35.0	-14.8±11.9	Intermittent
334	California	1964.0-1978.0	1973	-59±18	16.6±2.2	17.6	4.7±1.0	Intermittent
113	New Mexico	1972.0-1978.0	None	-89±10	-1.3±3.3	9.4	21.2±2.1	1976.5
111	Maryland	1964.0-1976.7	1973	-31±25	-47.6±4.8	-47.5	14.0±2.7	
192	Texas	1974.0-1978.0	None	-61±46	-26.3±6.5	-4.0	(2)	None
114	Alaska	1964.0-1976.0	1973	-59±20	5.4±4.4	18.6	29.6±1.8	1976.0
118	Greenland	1964.0-1978.0	1973	-35±19	-4.0±3.5	-7.0	19.2±1.6	1977.0
128	Ottawa	1975.3-1978.0	None	N.A.	-91.3±12.9	N.A.	(2)	1977.0
30414	Calgary	1975.0-1976.0	None	N.A.	69.1±7.8	N.A.	(2)	None
107	Virginia	1976.0-1978.0	None	N.A.	17.7±35.0	N.A.	(2)	None
SOUTH AMERICA								
8	Brazil	1964.0-1978.0	None	16±11	-15.1±3.8	-10.5	-9.9±2.2	None
EUROPE								
116	England	1971.5-1978.0	None	7±9	34.6±3.0	34.1	33.9±2.2	1976.0
21	Belgium	1972.3-1978.0	None	-7±7	20.6±2.5	13.5	(2)	None
641	Italy	1975.0-1978.0	None	N.A.	13.3±6.8	N.A.	(2)	None
AFRICA								
105	South Africa	1965.0-1978.0	None	-60±11	-18.4±3.3	9.2	10.5±1.9	None
20	Seychelles	1965.0-1978.0	1973	-9±19	-30.4±3.0	-24.7	-6.4±1.8	None
ASIA								
27	Japan	1964.0-1978.0	None	N.A.	25.3±3.4	31.8	21.3±1.7	1974.2
22	Phillipines	1964.0-1978.0	None	10±29	10.3±6.0	28.2	9.2±2.5	None
PACIFIC								
340	Hawaii	1964.0-1978.0	1973	-113±28	7.4±3.0	13.2	-5.9±1.2	None
117	Samoa-1	1964.0-1973.0	1973	89±29	N.A.	N.A.	-1.2±7.0	1973
24	Samoa-2	1974.0-1978.0	1973	N.A.	-81.3±6.0	N.A.	(2)	1973
[illegible]	Guam	1974.0-1978.0	None	-74±32	-55.2±6.0	N.A.	(2)	None
AUSTRALIA								
112	Adelaide	1964.0-1978.0	None	14±6	2.7±1.7	14.2	21.4±1.2	None
ANTARCTIC								
19	McMurdo	1965.6-1978.0	None	-52±19	7.2±5.8	7.4	60.1±4.0	None

NOTES: N.A. - Not applicable or not available due to short data span.
(1) - Station was not actually moved but different antennas are used.
(2) - Same as 1972.0-1978.0 because station started operations after 1972.0

Table 3. Station Coordinate Changes
Over 14 Years (cm/yr)

STATION	LONGITUDE	LATITUDE	HEIGHT	NUMBER OF SOLUTIONS
NORTH AMERICA				
Maine(1)	6.4±1.8	15.9±1.5	2.9±1.6	331
Minnesota(2)	-22.8±2.0	-5.9±1.3	-14.8±1.9	398
California	2.5±1.6	-1.3±1.1	4.7±1.0	373
Maryland(1),(2)	4.4±2.0	4.4±1.4	14.0±2.7	259
Alaska(1),(2)	10.1±1.6	-9.0±1.2	29.6±1.8	237
Greenland(1),(2)	-10.5±1.1	6.2±1.1	19.2±1.6	296
SOUTH AMERICA				
Brazil	-3.4±2.1	-7.6±2.0	-9.9±2.2	347
AFRICA				
South Africa	2.4±1.8	-10.6±1.3	10.5±1.9	378
	-8.6±2.1	0.7±0.6	-6.4±1.8	322
ASIA				
Japan	1.9±1.8	0.1±1.6	21.3±1.7	410
Phillipines	-6.3±2.0	-7.2±2.0	9.2±2.5	313
PACIFIC				
Hawaii(1)	3.8±1.9	9.8±1.2	-5.9±1.2	328
AUSTRALIA				
Adelaide	-14.2±1.3	12.7±1.0	21.4±1.0	397
ANTARCTICA				
McMurdo	-23.7±3.4	-0.2±3.8	60.1±3.5	286
RMS	11.0,1.9	8.1,1.7	15.1(3),1.6	

NOTES: (1) 1973 data not processed
(2) station closed or moved one to two years before end of data span
(3) excluding Antarctica

Table 4. RMS Residuals from NWL 9Z-2 Coordinates (cm)

	Longitude	Latitude	Height
NORTH AMERICA			
Maine	110	106	148
Minnesota	130	63	106
California	93	52	64
New Mexico	87	64	93
Maryland	99	57	132
Texas	118	63	121
Alaska	92	45	74
Greenland	66	56	88
Ottawa	119	73	141
Calgary	121	118	96
Virginia	90	137	86
SOUTH AMERICA			
Brazil	99	77	115
EUROPE			
England	97	56	197
Belgium	84	57	79
Italy	97	66	64
AFRICA			
South Africa	101	65	105
Seychelles	107	65	97
ASIA			
Japan	100	93	109
Phillipines	118	97	151
PACIFIC			
Hawaii	108	67	86
Samoa	114	102	176
Guam	107	64	193
AUSTRALIA			
Adelaide	96	49	52
ANTARCTIC			
McMurdo	129	136	204
AVERAGE	103	76	116

Table 5. Potential for Improvement

	Significance	Implementation Cost	Operational Cost	Special Effort	Requires Study
3. Orbit					
Gravity field	H	H/L	M	N	Y/N
Misc orbit changes (ocean, atmosph., land tides)	L	L	L	N	N
Process more satellites	M	N	H/N	Y/N	N
Re-process old data	H	N	H	Y	N
Use drag-free satellites	M	M	N	Y	Y
1. Rubidium Oscillator for Geoceiver	M	N	N	N	N
Reprogram	M	H	N	N	Y
Tropo bias parameter	H	N	N	N	N
2nd order ionospheric correction	M/N	M/L	M/L	Y	Y
Longer count interval	M	L	L	Y	Y
Biased range	M	L	L	Y	Y
Orbit bias	L	M	L	Y	Y
Process more satellites	M	N	M	N	Y
Process available data for more stations	H	N	M	Y	Y
Re-process old data - New orbits	H	N	M	Y	N
- Current orbits	H	N	M	Y/N	N
5. Review Survey Records	H	N	L	Y/N	N
6. Rate Computations					
Simultaneous treatment of data	H	L	L	Y/N	N
Consider survey connection uncertainty	M	L	L	Y/N	N
2. Data Acquisition					
Encourage more stations	H	N	L	Y	N
Maintain fixed network	H	N	H/L	Y	N

Key: H, M, L are high, medium, low.
Y, N are yes and no or none.

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